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Drinking Water Supply System using Solar Power

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Abstract

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The current water supply system in Las Delicias consists of 75 hp (56.25 kW) pump system. It was determined that a re-design of the hydraulic system was necessary to reduce power requirements. The new design added a new holding tank and eliminated the need for a 60 hp booster pump, reducing the total pump power needs to 34 hp (25.5 kW). This design allows the villagers to receive continuous water. The total investment of this new design is $120,000 and yields a NPV of $413,000 (at 1.6% discount rate) and an IRR of 36%.

The system in Apatut is a grass roots project. We worked with the initial design provided by the EWB-MAP team that is currently involved with the project. The total investment is $22,000 and yields a NPV of $78,000 (at 1.6% discount rate) and an IRR of 41%.

Department of Chemical and Biomolecular Engineering
University of Pennsylvania

Drinking Water Supply System using Solar Power

Senior Design Report 2011

Renata Bakousseva, Hessa Darwish, Hall Sun

April 12, 2011

DRINKING WATER SUPPLY SYSTEM USING SOLAR POWER

Design group:

Renata Bakousseva

Hessa Darwish

Hall Sun

Advised by:

Dr. Sean Holleran

Professor Leonard Fabiano

Project suggested by:

Adam A. Brostow

Senior Design Report

April 12, 2011

University of Pennsylvania

Chemical and Biomolecular Engineering

University of Pennsylvania
School of Engineering and Applied Science
Department of Chemical and Biomolecular Engineering
220 South 33rd Street
Philadelphia, PA 19104

April 12, 2011

Dear Mr. Fabiano, Dr. Holleran, and Adam Brostow

Enclosed is our proposed design for the *Drinking Water Supply System using Solar Power* problem statement provided by Adam A. Brostow of Air Products and Chemicals, Inc. Our solution includes three main parts for the villages of Las Delicias, El Salvador and Apatut, the Philippines. The three main parts consist of: redesigning the hydraulic system, introducing solar power, and rainwater harvesting as a future recommendation.

The following report details the design process, the equipment needs, estimated costs, the utility requirements, and a detailed economic analysis. This is included for Las Delicias, El Salvador and Apatut, the Philippines. The process is designed to operate for 20 years with replacements. This was based on the lifetime of the photovoltaic modules.

Our proposed process design yields a NPV of $413,000 and an IRR of 36% for Las Delicias, El Salvador. The NPV for Apatut, the Philippines is $78,000 with an IRR of 41%. Detailed economic analysis, including sensitivities to key input assumptions have also been included and discussed.

Sincerely,

Renata Bakousseva

Hessa Darwish

Hall Sun

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Abstract

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PROJECT CHARTER

Project Charter

Project Name	Drinking Water Supply System Using Solar Power
Project Champions	Mr. Adam A. Brostow, Professor Fabiano, Dr. Sean Holleran
Project Leaders	Renata Bakousseva, Hessa Darwish, Hall Sun
Specific Goals	Development of an affordable and sustainable power supply system for powering water pumps
Project Scope	In-scope: • Sustainable power source • Affordable power source • Power source must have maintenance costs less than $30,000 a year (Las Delicias) • New pump selection Out-of-Scope: • Re-design of piping system
Time Line	Completed in four months

INTRODUCTION

Currently, 884 million people in the world live without access to clean water sources. More than 1.2 million children die each year as a result of water borne diseases such as diarrhea, malaria, and trachoma [1]. Access to clean water supplies is a central target in the UN Millennium Development Goals. The need for alternative, affordable, and safe drinking water supplies is critical if poverty is to be reduced and an environment conducive to progress is fostered [2]. As one of the steps towards reaching this goal and making clean water both available and affordable, Engineers Without Borders (EWB) set out to provide clean water for two villages: Apatut, the Philippines and Las Delicias, El Salvador.

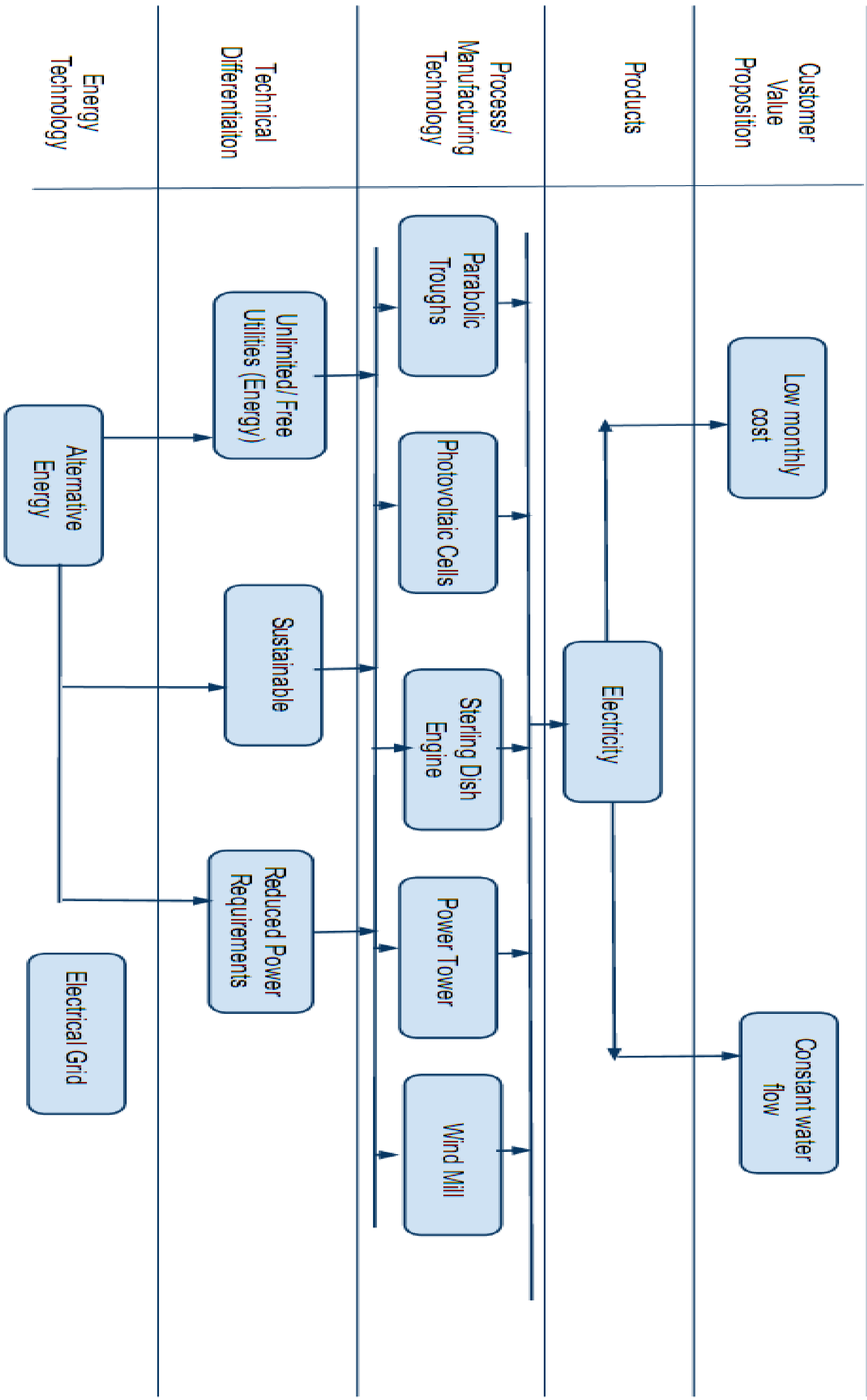
Apatut, the Philippines

This design project involves supplying clean water to Apatut, a small village in the Philippines located approximately 200 miles north of Manila. Currently, there is no form of centralized water distribution in Apatut; rather, the villagers have to walk to several wells and small creeks within the surrounding area to collect water. Because the water is obtained from shallow wells, the water quality is poor and often contains impurities that rise to the surface of the water. This creates a high risk situation for the villagers, as the water they acquire is contaminated and could lead to water borne illnesses. As a result, the EWB teamed up with Rotary Clubs in the area to initiate a "Water for Life" project. The purpose of such a project is to provide clean and affordable water for the villages. This senior design team focused on finding low-cost and sustainable sources of power supply for the water pump. In doing so, we assessed pump design, power requirements, and finally selected the appropriate power source. Our goal was to focus on using a form of energy that will avoid reliance on the electrical grid and reduce costs to the villagers. Our final recommendations include the use of solar power as the alternative to the grid.

Las Delicias, El Salvador

Las Delicias is a small village located 30 miles from the capital San Salvador. This design project differs slightly from the one in Apatut as we are improving an existing water supply system. The current system in Las Delicias consists of a submersible pump and booster pump, the latter of which pumps water to two holding tanks located two miles away at an elevation approximately 560 feet above the booster pump. The third holding tank contains water fed from a mountain spring that is being distributed to all tanks through a pipeline. Grid electricity is currently the sole power source. The villagers receive water for only certain hours during the day three times a week in the dry seasons and twice a week in rainy seasons. The water is distributed by gravity and directed to each house's water tap stand. This water distribution schedule is a consequence of the high electric bills derived from remotely supplied electricity. Because of high electricity costs, the residents of Las Delicias cannot receive continuous access to water. The goal of our design project is to alleviate electricity costs so that the villagers can receive water daily. To do this we have proposed a new design that reduces power requirements as well as recommends a solar alternative to the power grid.

INNOVATION MAP


Customer Value Proposition
Products
Process/ Manufacturing Technology
Technical Differentiaiton
Energy Technology
Low monthly cost
Constant water flow
Electricity
Parabolic Troughs
Photovoltaic Cells
Sterling Dish Engine
Power Tower
Wind Mill
Unlimited/ Free Utilities (Energy)
Sustainable
Reduced Power Requirements
Alternative Energy
Electrical Grid

System Components

Power Supply System

Photovoltaics

Photovoltaic solar panel (PV) is a method of generating direct current electricity by converting solar power using semi-conductors that display the photovoltaic effect. The magnitude of energy provided is dependent on the amount of photovoltaic material available to harness solar energy, and on the intensity and duration of sunlight. Within a single photovoltaic panel, a number of cells containing the photovoltaic material generate voltage by transferring electrons between different bands (valance to conduction) causing a buildup of voltage between two electrodes (see Figure 1 on page 16). Sunlight serves as the radiation source as it is composed of photons, which are packets of solar energy. The radiation energy may either be reflected or absorbed upon contact with a PV cell; those that are absorbed generate electricity. An anti-reflective coating is applied to the surface of solar PV cells to reduce the instance of photons reflecting off. The photon absorption process follows the principle of photoelectric effect, whereby the absorbed photon transfers its energy is to an electron in the atom of the semiconductor. This electron is able to dissociate from the atom due to its excited energy state and is ejected from its place, producing current in an electrical circuit. The PV cell contains a built-in electric field that provides the voltage required to drive the current out through an external load [3]. This electric field is created by the differences in treatment of the thin layers of the solar cell. Treatment with impurities called dopants causes one region, the "n-type", to contain an excess of electrons while the other "p-type" region has an excess of positive holes. A solar cell consists of a wafer of p-type silicon with a layer of n-type on top (see Figure 1). Dopants have the effect of replacing elements in the crystal lattice of the semi-conductor; within silicon, boron is used as a dopant for the p-type while phosphorous is used as the n-type dopant. This n-p junction produces an internal electric field that is able to capture electrons ejected by solar radiation; as the electrons move toward the n-side of the solar cell, the positive holes move toward the p-side causing an electromotive force within the semiconductor. When connected on both sides to conductors an electrical circuit is formed and electrons are utilized in the form of electric current. Because the flow of solar radiation is continuous throughout the daylight hours, the current produced by solar cells is uninterrupted and results in direct current (DC). Currently, some materials used for photovoltaics include silicon (monocrystalline, polycrystalline, and amorphous), cadmium telluride, and copper indium selenide/sulfide [4]. Due to cost and availability concerns, photovoltaics utilizing monocrystalline silicon was chosen for the solar power system in both Las Delicias and Apatut.

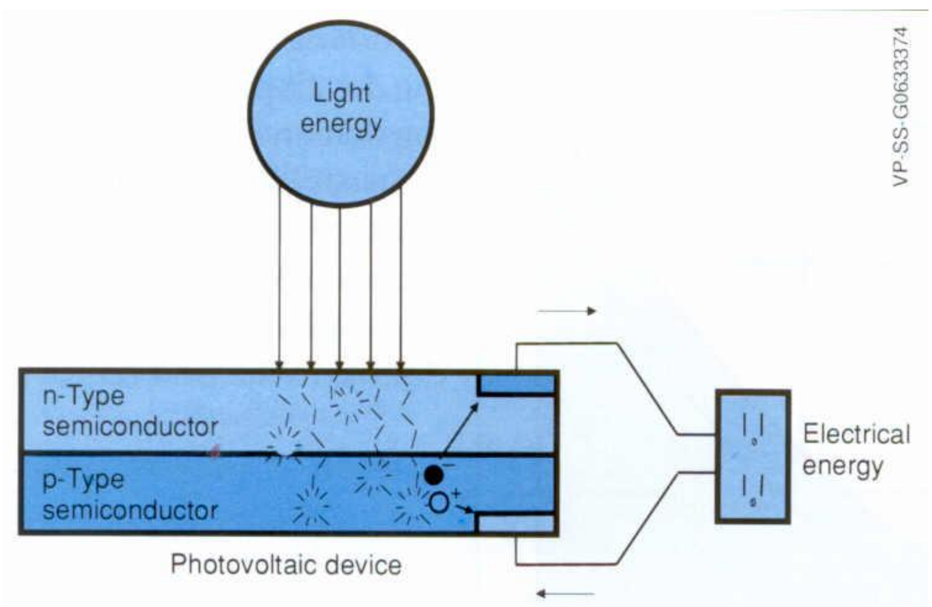


Figure 1: Diagram of photovoltaic effect within a photovoltaic cell. The photons are absorbed and energy is transferred to the valance electrons in atoms of the material. Electrons that have absorbed enough energy to each an excited state break from the forces of the atom and the electric field of the cell provides the voltage necessary to drive the current of electrons through an external load.

Combiner

The solar array combiner box is an integral part in the system that works similarly to a junction box. The conductors used to wire the modules of the PV array are connected to the combiner, which reduces the voltage drop. This also reduces the amount of wiring necessary to connect the PV array to the charge controller and provides a way to combine all the photovoltaic circuits. In addition, the combiner box allows for removal and repair of a single module within the entire array without interrupting the entire system, decreasing the possibility of a complete power system failure. The combiner box also contains fuses, equipment grounds, grounding terminal strip and electrode conductor, as well as a lightning arrestor [5].

Charge controller

From the combiner box, a single output is then connected to the solar charge controller. The controller regulates the voltage and current from the PV array as the voltage of PV panels vary depending on the incident insolation at different times of the day. A controller is necessary to ensure the battery is not overcharged with excess voltage, thus damaging the battery and compromising the entire system. Different controllers are commercially available; however, most are not suitable for large scale photovoltaic power systems as they limit the power output of the panels by reducing the voltage without an increase in current. A solar panel can only output a maximum amount of current and a decrease in voltage will result in a direct decrease in power, lowering the efficiency of the system as a whole. Maximum Power Point Tracking (MPPT) controllers solve this problem by tracking the optimal voltage of the panels to maximize the amperes to the battery. The output varies continuously as the voltage and current are adjusted by the controller. MPPT controllers have efficiencies around 94% to 97% and are most effective during the winter or on cloudy days when power from the sun is limited and loss cannot be tolerated.

Inverter

A solar inverter is a necessary component of any solar system providing energy to AC circuit loads since the output of solar panels is DC while most equipment is AC powered. A grid tie inverter is a device that converts DC power to AC and then feeds this AC current into the electric grid. The locations of both of our systems impose political challenges to connecting the grid to solar power and any solar power produced must be used directly for the villages' needs. Hence, there is no need for a grid-tie inverter. An AC breaker panel is accounted for further along the electrical system to connect the grid to the pumps as a backup in case of a malfunction in the power system.

The inverter performs three major functions: inversion of the power, Maximum Power Point Tracking (MPPT), and finally integration and packaging. Within the inverter a set of solid state switches flip the DC power back and forth continuously creating AC power. Figure 2 on page 19 below shows the basics conversion from DC to AC power.

Like the charge controller, the inverter also performs the function of maximum power point tracking. Integration and packaging consists of the balance of the components of the inverter, including AC and DC disconnection means (manual and automatic), transformer, cooling system, LCD display and finally communication connections for monitoring [6]. The voltage will be flipped from 48 VDC to 220 VAC, the required voltages for the pumps. The inverter cost is included in the BOS estimate of both systems as $500; however, it does require replacement every ten years.

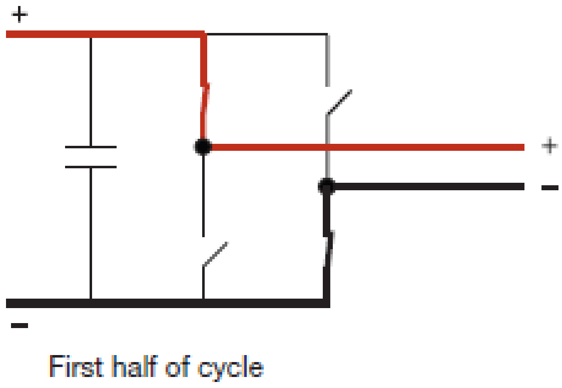


Figure 2. Basic diagram of an H-bridge circuit which performs the conversion from DC to AC power. The two halves of the cycle continuously flip the DC power, creating the alternation inherent in AC power.

AC Breaker Panel

A wall mounted AC breaker panel is the point at which the three pumps' electrical wiring will meet with the electricity provided by the solar power system. In addition, this provides a place for the grid to be connected to the pumps as well in case of a shortage of solar power. This breaker panel does not need to be the size of a typical house panel as the system only demands three outlet breakers and two inlet ones. Here, other loads can also be attached for times when solar power exceeds the needs of the pumps as detailed in Average Insolation section of the Appendix. The breaker box will be sourced from New England Solar Electric, Inc. at a cost of $169. The box consists of one 2-pole main breaker and six circuit breakers, more than is needed for the solar power system.

Batteries

The use of photovoltaic panels as the primary energy source necessitated the consideration of electrical storage for pump use during the night time or on cloudy days when solar power was not readily available. Inclusion of a battery would also significantly reduce energy waste during inevitable spans of increased solar intensity when more power than the system needs is provided. The electrical energy requirements for the power systems implemented were stringent and specific: a battery must store large amounts of energy, in the order of tens of kilowatt hours, must able to discharge daily, and must be resilient under non-ideal storage conditions was necessary for the application of solar energy use. Although most battery types were considered, it was determined that the most suitable are deep cycle lead acid batteries [7]. These batteries are designed for longer life and are able to cycle as deep as 80 percent of rated capacity [8]. The configuration of the batteries matter as well. Through research conducted by Cassaca et al. (1996), it was concluded that the dual battery configuration minimized energy waste and improved efficiency by treating the batteries as separate entities. This configuration was able to charge the battery that was not being used while simultaneously utilizing the battery under load.

Pump criteria

Centrifugal pumps

Several types of pumps were considered but the ultimate choice rested with AC powered centrifugal pumps. This coupling of AC and centrifugal is able to provide high flow rate at high heads, both important requirements for the systems in Las Delicias and Apatut. Additionally, because both systems have deep wells in place, there is a need for a deep well submersible pump, which may only be provided by pump of centrifugal design. For more on pump selection and the other alternatives considered, please refer to the section on *Alternative Analysis* on page 87.

Water-pump schedule

Determining daily water demand

The acceptable daily rate of water consumption is difficult to estimate. Different sources have their own figures for “minimum” daily water usage. The US is one of the heaviest users of water, consuming as much as 78 gallons per person per day for bathing, drinking, cooking, etc.

The Netherlands has been able to bring down its average daily water consumption to about 27 gallons per person [9]. Places in other parts of the world use significantly less water either due to conservation reasons or simply because a very limited supply of water is available.

After consulting several sources, it was determined that the minimum daily water usage per person is approximately 13 gallons per day [9]. This includes cooking, drinking, sanitation and bathing. Las Delicias consumption is expected to be lower because of their lack of access to proper sanitation and bathing facilities. However, providing them with minimum water is also not desired, so we used an estimate of 25 gallons per person per day, slightly lower than the number in the Netherlands and twice as much as the established minimum of 13 gallons per person per day. This is also close to the daily water usage per capita in Apatut, which was provided in the project statement as 30 gallons per capita per day.

In determining the water schedule for the villagers, we estimated hourly needs based on two sources: a typical US water usage for different times of the day [10, 11], and hourly water usage of one Pilipino worker from Manila [12]. Although the numbers will be somewhat different for our systems, the general percentage of water use for various purposes is similar and is summarized in Table 3 on page 22 by use and time of day. This breakdown of hourly water consumption was used in both the Philippines and in El Salvador. Table 3 is divided into three major sections: early morning, afternoon, and evening. During the early morning the proportion of water used steadily increases as more people wake up and go about their daily business. Water is used for food preparations, hygiene and drinking. The highest proportion of water is used during the evening hours because that is when people might want to perform their hygienic needs after a long day of work (e.g. bathing, large dinner, etc). All of the calculations with regards to the daily and hourly loads on the tanks and the pumps were based off these estimates.

Table 3. Daily water use, broken down by the hour.

Time of day	% of water used	Reason for water use
6	3%	Shower
7	3%	Toilet
8	4%	Breakfast preparations
9	7%	Drinking
10	7%	Miscellaneous
11	7%	Lunch preparations
12	7%	Toilet
13	5%	Laundry
14	5%	Drinking
15	5%	Miscellaneous
16	5%	
17	9%	Dinner preparations
18	9%	Toilet
19	9%	Shower
20	9%	Drinking
21	3%	Miscellaneous
22	3%	

Pump use schedule

In order to determine the optimal pumping schedule to provide an uninterrupted supply of water that would satisfy the water demands of the two villages, alternative pumping schedules were determined. The two extremes of the possibilities in pumping schedule are directly related to the solar power supply. It is possible to pump only using photovoltaic panels as energy which would limit pumping to the nine hours of daylight each day. On the other extreme is the use of PV panels combined with a bank of batteries to store energy for night pumping. Although continuous pumping is theoretically possible, a schedule of 22 hours of pumping throughout the day was considered as it leaves time for maintenance and cleaning. Pumping only nine hours a day represents the largest possible gallon per minute requirements for the pumps and pumping for 22 hours a day equates to the lowest water flow rate. With the flow rate requirements determined, rough estimates of power requirements were determined and finally the total costs of the system was estimated using pump costs and the cost of PV modules and batteries. From there, the best possible pump schedule was chosen based on the lowest cost. The details of the different scheduling models for system are discussed in the sections dealing with individual project sites.

PROJECT SITES

Las Delicias, El Salvador

Addressing the problems of the current system

The water supply system in Las Delicias, El Salvador is currently comprised of two pumps connected in series. A 15 hp (11.25 kW) submersible pump moves the water from the well into a small holding tank at the surface of the well. A 60 hp (45 kW) booster pump moves the water from the holding tank into the two distribution tanks (see Figure 4). Having two pumps in series is not the most ideal system design because the flow rate of the water is not always steady and the variations in the flow rate result in variations in power consumption of the pumps. Furthermore, variable flow rates could lead to dry pumping and cause significant damage to the pump motors. Variable Frequency Drive (VFD) control can solve this issue. VFD is a type

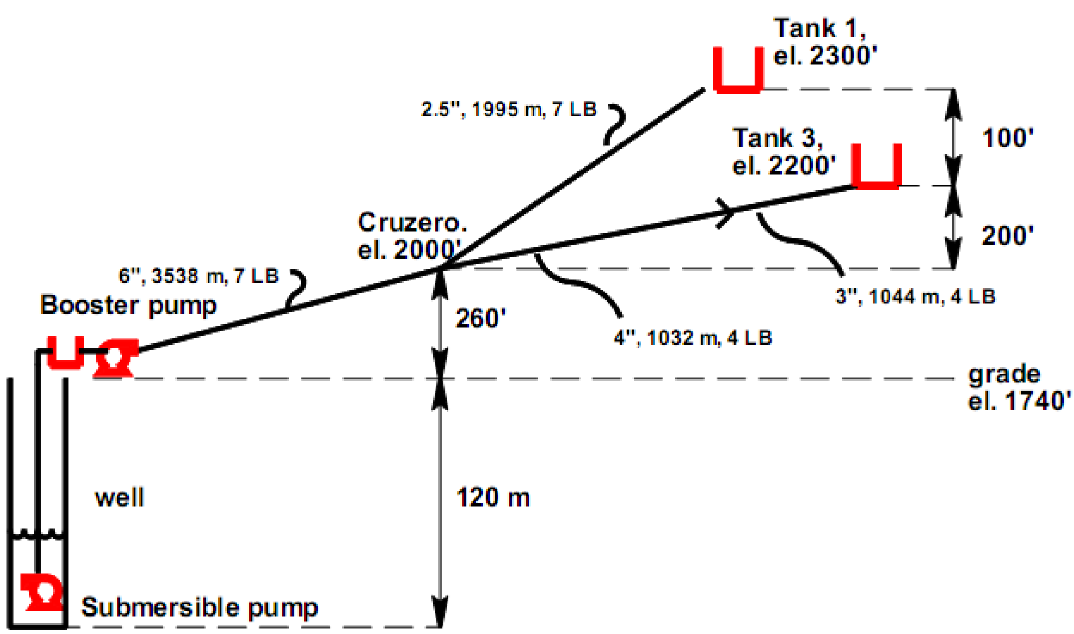


Figure 4. Las Delicias, current water supply system. The design is comprised of a submersible pump, one booster pump, and two tanks connected to the pumps. An additional tank is located at an elevation between tanks 1 and 3. It is not shown because it is not connected to the pump system, and instead obtains its water from a local mountain spring source.

of automatic flow control that controls the pump power and consequently the flow rate output. It can be used to prevent dry pumping of the booster pump. An additional benefit to VFDs is the associated energy savings. By setting a limit on the flow rate, it regulates the power provided to the pump and thus eliminates unwanted variations in power consumption. One disadvantage with VFDs is that the cost of the system scales up with horsepower. Typically, this type of control starts at $3,000 for 5 hp (3.75 kW) and increases in price all the way to $45,000 for a 300 hp (225 kW) system [13]. The 75 hp system in Las Delicias could cost as much as $12,000 for VFD control [14].

A combination of solar power and a VFD flow control is the ideal low intervention solution to the problem of high electricity cost, limited water supply in Las Delicias. However, while this solution satisfies the project objectives, it does not provide the community with the best possible option for the water supply system. The costs associated with powering and controlling a 75 hp system are significant with respect to solar PV modules and the VFD flow control. The immense land usage with regards to PV modules also cannot be ignored. A further analysis of the entire system yielded several other options which may better fit community needs. More specifically, an examination into a modification of the hydraulic system in Las Delicias has demonstrated great potential in improving water distribution and lowering pump power requirements, the latter of which will lower energy bills and the overall investment cost of the project.

New system design

Re-designing the hydraulic system

Implementing a new tank and selecting its location

The current system must overcome several challenges, including poor water distribution (as some households rarely get water) and high power costs. Having this new tank in place will help solve the distribution issue that some residents have been complaining about [15]. The gravity fed distribution system in place for both tanks 1 and 3 creates water distribution inequality. The population is spread out over an elevation difference of 560 feet, with the residents at the bottommost elevations not getting enough (or any) water because it has been taken up by the residents closest to the tanks, where flow is higher and the water reaches the pipes sooner. A new tank between the well and tanks 1 and 3 will solve this problem by distributing water to the lower half of the community. Based on a community wide assessment performed by the EWB team, approximately 33% of Las Delicias residents live between the well site (elevation of 1740 feet) and the midway elevation point of 2,000 feet. The rest of the residents live at an elevation between 2,000 and 2,300 feet, closest to tanks 1 and 3 which sit at 2300 feet and 2200 feet, respectively. Placing the new tank at 2,000 feet could result in better water distribution for the community, with 33% receiving water from the new tank, 20% receiving water from tank 3, and the rest from tank 1. This elevation would also be ideal because it is the point where the Cruzero Crossing of the pipes is located. At the Cruzero, the pipe that delivers water from the well splits into two main branches, one that leads toward tank 1 and another that goes to tank 3. Placing the tank right before the crossing point will facilitate the incorporation of the new tank into the old system since two different pipelines will be available to pump water to the two tanks already in place.

The power costs are directly related to the large power requirements of the two pumps currently in place. The combined power needs for both pumps are 75 hp (56.25 kW), with the 60 hp (45 kW) booster pump being the heavier user of energy and accounting for 80% of the electricity used to power the pumps. Eliminating the need of the 60 hp (45 kW) pump and thus decreasing the pump power requirements would be an ideal solution for cutting power consumption. There are several options of how to do this, one of which is digging a new well atop the hill where tanks 1 and 3 are housed. Having a new well in place at the top will greatly reduce the total dynamic head (TDH) the pump will need to overcome, thus significantly reducing the pump size. This is a risky endeavor and does not guarantee water; it is very likely to result in significant money loss with no result to show for it. Furthermore, it does not address the water distribution issue that the residents currently face. A better option would be to increase the size of the holding tank and move it uphill, thereby using it as an intermediate tank between the well and tanks 1 and 3. This option could eliminate the need of the booster pump, relying just on the submersible pump to move the water from the well to the intermediate tank. Two small booster pumps would then be used to pump water from the new tank to tanks 1 and 3.

There is an additional option for using just one booster pump to move water from the new tank to the current tanks. This would eliminate the costs associated with buying and maintaining two booster pumps. However, we decided that having two booster pumps will add important flexibility to the new system. In the case that the booster pump happens to break, both tanks 1 and 3 will not be able to obtain well water. This will place great water strain on the community because the new tank is only able to hold 20,000 gallons, a fourth of the total residents' daily needs (see the next section for a discussion of sizing a tank). Alternatively, if there are two distinct booster pumps for tanks 1 and 3, having one break is less of a concern because it would mean that only one tank is out of water. Having two tanks with a maximum capacity of 55,000 gallons (if tank 1 is in action) or 45,000 gallons (if tank 3 is in action) is a better alternative to having just one tank and 20,000 gallons available. Thus, we decided to sacrifice cost savings associated with installing just one booster pump and designed a system equipped with two booster pumps. The final system design is shown in Figure 5 on page 30. It includes tank 2, which is unconnected to the supply system and obtains water from the local mountain spring.

To explore this option further and to determine whether the 60 hp (45 kW) booster pump can actually be eliminated, we performed a system analysis and accounted for the head associated with elevation differences, pipe friction, and friction loss in the pipe fittings. The analysis was divided into three parts: the first part concerned itself with the pipeline leading to the new tank, while the second and third parts looked at the booster pumps for water supply to tanks 1 and 3.

The general form for calculating the total dynamic head (TDH) was as follows

$$TDH = Static\ Lift + Static\ Height + Head\ Loss$$

The static lift refers to the height the water needs to rise before reaching the pump. The calculations concerning the submersible pump resulted in a static lift of zero, accounting for the fact that the pump will be completely submerged in the water inside the well. Assuming that the booster pumps will be placed close to the new tank and on the same elevation, the static lift for the booster pumps calculations was also presumed to be zero.

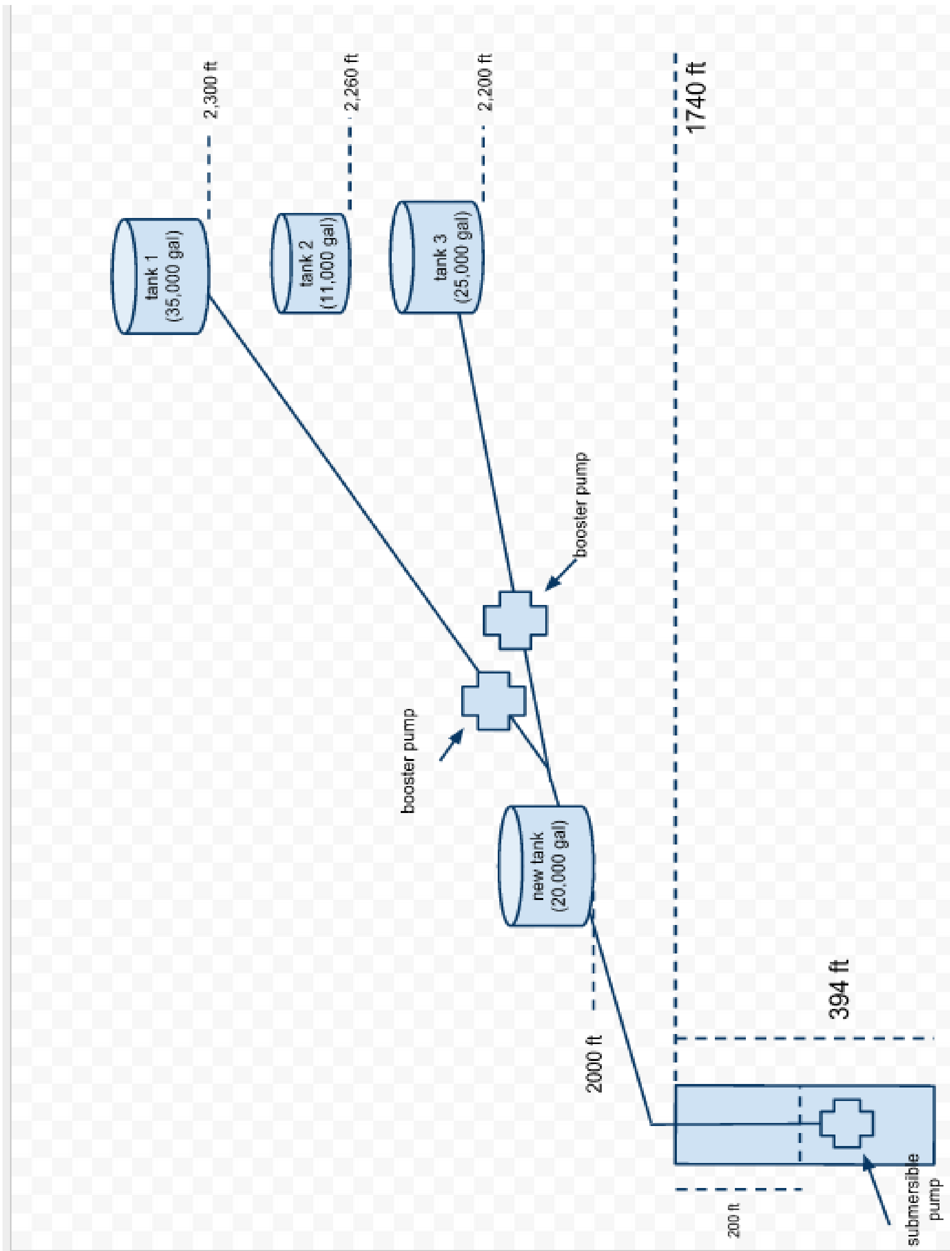


Figure 5. The new design for the hydraulic system in Las Delicias, El Salvador. This design incorporates a new holding tank at the elevation of 2,000 feet, roughly the half way elevation between the well and the highest point in the village where tank 1 is located. Two additional booster pumps are added to provide water for tanks 1 and 3.

The static lift refers to the height the water needs to rise before reaching the pump. The calculations concerning the submersible pump resulted in a static lift of zero, accounting for the fact that the pump will be completely submerged in the water inside the well. Assuming that the booster pumps will be placed close to the new tank and on the same elevation, the static lift for the booster pumps calculations was also presumed to be zero.

The static height accounts for the height the water must rise after leaving the pump. Essentially, this is the elevation difference between the pump and the tank.

Head loss takes into account the added pressure on the system due to friction in the pipes and in the pipe fittings. Since pressure drop in pipes is a function of fluid velocity, this part of the TDH calculation determines the sensitivity of the system to the water flow rate. Generally, higher water velocity through pipes creates a stronger resistance to flow, thereby increasing the head loss. Increased head loss results in a higher overall TDH and consequently a greater pump power requirement.

Tables A1 through A3 (see pages 122-124) display the various components of TDH, including static height and head loss due to various piping sections and pipe fittings. Because detailed data of the piping system was not available, we estimated the number of fittings in the system. The head loss associated with pipe fittings did not significantly affect the final TDH, accounting for less than 1%; hence, we were confident in our estimation technique and did not focus on precise details regarding the pipe fittings. Because TDH is a function of fluid velocity (due to the head loss factor), several other components were included in its calculation, including Reynolds number, Fanning friction factor for turbulent flow and the fluid velocity and volumetric flow rate (all of which were used to determine head loss. For sample calculations and a list of equations A5-A9 on pages 152 and 153.) A system curve was generated for each part of the hydraulic system. The system plot for the first section of piping (which is related to the submersible pump) is shown below in Figure 6; the rest of the plots are included on pages 125 and 126 (Figures A4 and A5). Note that the Darcy-Weisbach equation listed on page 152 demonstrates a quadratic velocity dependence of head loss. Since head loss is a significant component of TDH, we expect TDH to also vary quadratically with flow rate. Looking at Figure 6 we can see the sensitivity of TDH with respect to the water flow rate: TDH increases as a function of velocity squared, as predicted by Darcy-Weisbach. Given this correlation between TDH and flow rate, we had to be careful in selecting the flow rate so as not to incur any additional head loss (which would increase pump power demand).

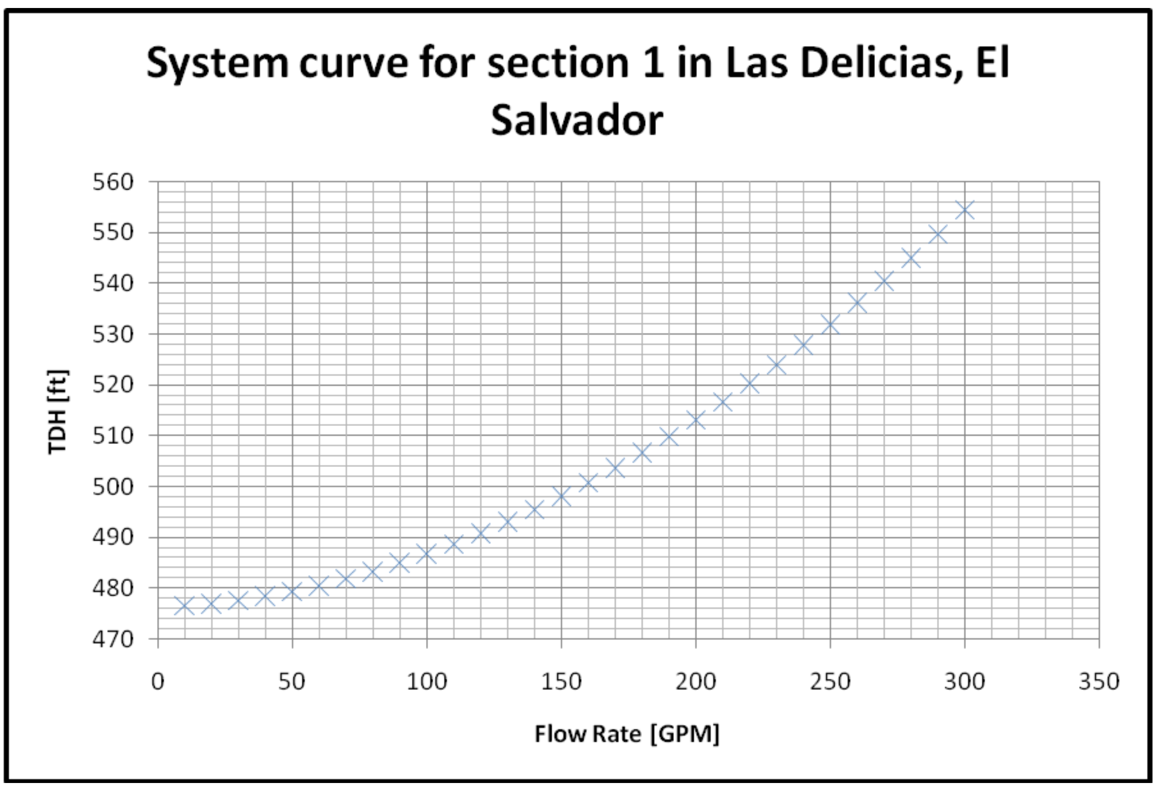


Figure 6. System curve for the piping section from the well leading to the new tank. As expected, the TDH varies quadratically with flow rate. Las Delicias, El Salvador.

Sizing the tank

The two tanks currently placed in Las Delicias have a capacity of 25,000 gallons and 35,000 gallons. These tanks are quite large and hold more volume that is needed given the new system design. To avoid extra costs associated with building a largely oversized tank, we sized the new tank based on maximum accumulation in our pumping schedule. The estimated amount of water being pumped every day is 80,000 gallons. This is based on the estimation that every individual requires 25 gallons of water a day, multiplied by the total population of 3,000. From this we were able to obtain the total amount of water that needed to be pumped as 75,000 gallons/day, adding 5,000 extra gallons to account for underestimation of daily water consumption. In the estimated water schedule, the pump will work for 12.6 hours each day, pumping at the GPMs specified previously. To start with some water in the tank, we designed the system to pump 8,000 gallons for 2 hours the day before to prevent the risk of having an empty tank.

Each day the tank starts at approximately 8,000 gallons; the water is being both drawn off by the residents and input into the tank by the pump. At some point of the day, the amount withdrawn is at a minimum. When this occurs the tank is at its maximum volume of the day. This number was tabulated from finding the difference between gallons accumulated and gallons withdrawn. For Las Delicias, we determined this difference to be 12,393 gallons. This value tells us that the tank size must hold at least 12,393 gallons. Therefore, when sizing our tanks we decided to create a slightly larger tank to avoid problems with overflow especially since most of our numbers are overestimates. This meant that we would obtain a tank of roughly 20,000 gallons. Table 7 summaries the typical dimensions of a 20,000-gallon cylindrical tank.

Table 7. Geometry of Cylindrical tank

GEOMETRY	
Tank Material Type	Ferrocement
Nominal Inside Diameter	18.462 feet
Nominal Sidewall Height	10.00 feet
Deck Slope	1" rise to 12" run
Bottom Slop	Flat
Nominal Capacity	20,025 gallons
Usable Capacity	19,024 gallons

The materials required in building a water tank can be sourced from *Electrama*, a distributor of industrial construction materials in San Salvador, El Salvador. The materials list and cost are summarized in Table 8.

Table 8. Summary of costs

Materials	**Amount**	**Cost****
Cement	3,750 kg	$750
Sand	11,250	$500
Water	7,500 L	$500
Steel Wire	75 kg	$375
Steel Wire Mesh	75 kg	$300
Accessories	---	$1000
Labor	---	
Total	---	$5000

Cylindrical tanks were chosen because their shape minimizes the stress on a tank since stress is evenly distributed. These tanks also require less material to build than their square counterparts, resulting in lower costs.

The main incentive in this project is to seek adequate and cost-effective tanks. Since the scope of our project is to design a sustainable system we wanted to focus on designing an affordable system that can meet the demands of the villagers. Therefore we stressed that the tanks be made from local materials without compromising the integrity of the system. Furthermore, local materials mean that there is emphasis on local labor, which reduces costs.

This will influence human sustainable development, which is development that expands the opportunities and capabilities of all the villagers to enable them to sustain a prosperous society, as well as be economically independent from foreign investment.

In designing the ideal tank, three main factors were considered: cost, feasibility, and size. To address these components research was done on the type of tank that would optimize the system. A summary of the following tanks and types is displayed in Table 9 on page 36.

From Table 9 we were able to conclude that the most economical system for such a design would be the ferrocement tank. The ferrocement tank can be made easily using local materials. The advantage of such a tank over concrete tanks is that they are easier to build and require less skilled labor. Smaller ferrocement tanks are portable, and they are strong enough to hold capacities up to 300 gallons. This is ideal in cases where water from tank is not collected daily [16].

Table 9: Summary of Different Tanks and Cisterns including the cost and characteristics

Tanks/Cisterns	Positive Attributes	Negative Attributes	Price Range/gallon
Fiber glass	Light weight, long lasting, standard capacities range from 50-15,000 gallon tanks, durable, easily repaired, no leaks	Expensive, tanks for potable use need to be USDA approved with resin lining and must be opaque to inhibit algae growth	\$3-8
Polyethylene	Good for above ground-installation, inexpensive, lighter than fiberglass, easier to transport	Don't retain paint well, often in dark colors which absorb heat, therefore must be buried or shaded, fittings may leak	\$1-2
Wood	Attractive appearance, made of cedar or pine, lined with plastic to increase longevity, durable, Using redwood: contains no resins, high levels of tannin (natural preservative against insects and decay), good insulator	Redwood is expensive, not readily available Pine is more readily available and less expensive but not as durable	\$0.2-1.2
Metal	Cheap, easy to move, above ground-use	Large (range from 150-2500 gallons), old or recycled tanks may contain lead, bronze fittings should not be connected to tank-causes corrosion	N/A
Concrete	Versatile, permanent, decrease the corrosiveness of rainwater by leaching into the water, desirable taste imparted to the water by calcium in the concrete being dissolved in locations where there is slightly acidic rainwater	Leaking may occur	\$0.8-2
Ferrocement (steel and mortar composite material-built with concrete but have multiple layers of mesh embedded in mesh)	Developed in 3rd world countries to be relatively low cost and durable, cheaper than concrete, thin and strong walls	Will need maintenance and repair as cracks appear, painting is recommended to reflect the sun's rays, reduce evaporation, and keep water cool	N/A (can often be built from the villagers themselves) Wire mesh: \$20 Cement: \$8 Wire netting: \$5-20 Sand: \$2 Water: \$5 Total costs: \$60 for 250 gallon

Requirements

Tanks must be durable and watertight to avoid leakage. The tank size must hold the appropriate volume while being serviceable for at least ten to fifteen years, as replacements will be costly. Furthermore methods of handling overflow should be dealt with in a safe manner. This means that whenever the tank is full, water falling off or taken out should be performed in a manner that will avoid unwanted sediment. The water must be extracted in a convenient matter for the user and with minimum contact so as to avoid pollution.

Shape

The tank shape possesses very important criteria in determining the volume-to-surface ratio. This is worth examining in choosing the ideal tank as it influences the type of material used. An optimal shape would have a high volume to surface ratio because we want to obtain a greater volume, using less material. It is easier to construct tanks with straight edges rather than circular or rounded [17]. Another important factor that we considered is the stresses due to the stored water. Water has weight and produces stresses equivalent to 10kPA/meter, (1.45 psi/3 feet). Since pressure exerts a force perpendicular to a surface, in all tanks the highest pressure occurs at the bottoms of the tank pointing downwards. A similar conclusion can be made with the force of pressure on the walls. However, the shape of the tank can influence whether this pressure is maximized or minimized.

Cubical

A cubical tank is the simplest tank to build and requires less labor and less skilled labor. However, there are several drawbacks to this type of tank. The volume to surface ratio is low, which means that more material would be required to construct the actual tank. The stresses on the tank are unevenly distributed, especially near the edges, which may cause faster deterioration.

In a typical cubical tank the force of pressure works downwards at the bottom and outwards towards the walls. In such a configuration the stresses accumulate and eventually cause the tank to stretch. As soon as the tank begins to stretch it is no longer as durable and the material used for the tank becomes weaker. Figure 10 shows the typical stresses associated with such a shape.

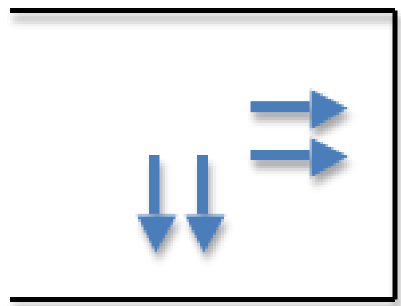


Figure 10: Typical stresses associated with a cubical tank

Pot Shaped

The second type of tank shape considered is the pot shaped which is doubly carved. Tanks of this type have a high volume to surface-area-ratio, which saves up on 20% of the material used to construct a cubical tank [17]. Due to the shape of such tanks, the decrease in diameter creates less stress on the material therefore the tanks are far more durable. The difficulty with such tanks is that they often require special moulds and a far more skilled labor force than building a cubical or cylindrical tank. As a result such tanks are expensive to build.

Cylindrical

A cylindrical tank has several advantageous over a cubical tank. The stresses on the tank are evenly distributed, with only increased stresses at the bottom of the tank. Instead of stresses acting towards the wall of a curved tank, stresses tend to act upwards. This is favorable because when stress acts upwards the tank is less likely to stretch and as a result is far more durable.

Compared to a cubical tank, less material is required to construct a tank of the same volume, saving about 7.5% on material [17]. This type of tank is more difficult to build when using bricks, but not when using ferrocement because the latter is more malleable. The disadvantage with this tank is that more skilled labor may be required. Figure 11 shows the typical stresses acting on a tank of that shape.

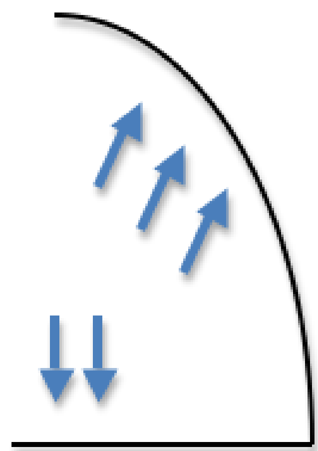


Figure 11: Typical stresses associated with a curved tank

To further investigate the stresses on a cylindrical tank, the Equation 12 must be introduced [18].

$$\sigma_h = \frac{pr}{t} \tag{12}$$

where:

σ_h= is the hoop stress,

p= pressure on the walls,

r= radius of cylindrical tank,

t=thickness of the tank.

Equation 12 defines the variable hoop stress. This type of stress occurs when a thin-walled tube or cylinder is subjected to internal pressure. The hoop stress is produced in the wall of the tank. This type of stress only occurs when the materials making up the tank are rigid. Therefore, it is ideal to have the tank be flexible or unconstrained. When this is not the case and the material of the tank is rigid, stress will cause the tank to bend because the material is constrained. Figure 12 demonstrates the phenomena of a constrained and unconstrained tank.

Figure 12: Movement of tank walls due to pressure. Unconstrained wall on the right and constrained wall on the left. (DTU,2001).

To avoid this type of constrained movement we focused on building a tank that would overcome the stresses. This was the reason we decided to use a ferrocement tank with a wire mesh lining. Such tanks have stronger form because they are thicker and thus can withstand such stresses. This will further avoid the cracking of the cement due to water pressure.

Given the following information, we have decided that for such a project where we must emphasize on savings and practicability, the cylindrical tank would be the optimal option. As can be seen the cubical shape fares badly in comparison to the other two tanks. More material is required with less storage space. It also has high stresses and more difficult to build with our chosen ferrocement material. The cylindrical shaped tank is the best option because it has fewer stresses in comparison and a better volume to surface ratio. Although the pot shaped tank is probably the ideal tank it requires greater skill and far better tools. Since the aim of our project is to use the villagers for labor to be "sustainable" we must rely less on skilled labor.

Selecting a flow rate

In El Salvador the inhabitants each require 25 gal/person/day for all daily water needs. With a population of 3,000 inhabitants, this equates to a total village need of 75,000 gal/day. The system is designed to provide 80,000 gal/day as to provide leeway for unexpected increases in demand or water shortages. For scenario one, (presented in Table A6 on page 127) it was calculated that the submersible pump needs to pump 150 GPM, the booster pump to tank one requires 44 GPM and booster pump to tank three needs 21 GPM to provide water to all three holding tanks. This scenario represents no battery use as all the pumping is done during the nine hours of daylight and power is supplied directly from the PV modules. Scenario three budgets for a continuous 22 hours of pumping a day, and requires only 60 GPM from the submersible pump, 18 GPM from pump one, and 9 GPM from pump to tank three (see Table A7 on page 128). This scenario minimizes the number of PV modules required, however, is reliant on the maximum amount of energy storage and thus the most batteries. These two scenarios represent the outer bounds of system design regarding the tradeoff between PV modules and batteries. In order to analyze scenarios combining the two, an iterative method was used. From scenario one, the amount of excess energy provided by the solar panels is calculated to be 148 kWh/day. This number is then divided by the kW requirement of the pumps to determine the extra hours of pumping possible if the excess energy were to be stored, 3.6 hours. This extra 3.6 hours of pumping is added to the nine hours of pumping originally accounted for in scenario one and new GPM requirements are calculated from the new 12.6 hours of pumping a day. Scenario two provides the GPM requirements of the three pumps for 12.6 hours of pumping each day (see Table A8 on page 129). Only 26 modules and eight batteries are required for the pump schedule detailed in scenario two. The iterative method is curtailed due to the lack of excess energy indicating the optimization of pump scheduling and balance between PV modules and batteries. These three scenarios were then compared on the basis of price and the most affordable, scenario two, was selected.

Selecting a pump

There are two main alternatives in pump selection: positive displacement (PD) and centrifugal pumps. Both positive displacement and centrifugal pumps and our method of pump type selection are covered in detail in the Alternatives Analysis section. Here we will focus on the details of selecting the appropriate centrifugal pump for the Las Delicias system.

As discussed in the *Alternative Analysis* section on page 87, centrifugal pumps are the most widely used pumps in the industry because of their ability to achieve continuous, high flow rate. Their major drawback lies in the dependence of the flow rate on the system head. Usually, higher head results in lower flow rate and the details of head and flow rate are specific to every pump; these are summarized in the pump performance curve of an individual pump. To determine the ideal pump for a particular system, the pump performance curve and the system curve are graphed on the same plot and their intersection point is considered the point of optimal operation for that specific pump within that system. This analysis was performed on all of the pumps selected for the El Salvador system. More than 20 different pumps were looked at and their performance curves were plotted against the system curve.

The plot of the submersible pump chosen for the El Salvador system is generated in Figure 13 below. It is a Franklin submersible pump, belonging to the 100SR6 series of pumps, and powered by a 25 hp (18.75 kW) Franklin motor. Looking at Figure 13 on page 44, the lightly shaded blue box represents the Best Efficiency Range of the pump and is the recommended range of pump operation. The red box outlines the desired range of flow rates for the submersible pump based on our own estimates (see *Selecting a flow rate* on page 41 for more details). As evidenced by the plot, the performance curve for the pump in question intersects the system curve at the point of (130, 500), within both the desired flow rate range and the best efficiency range, indicating that at 500 feet this pump is able to move water at the rate of 130 GPM. This head and flow rate are more than what is needed for the system. However, it is important to consider the fact that this is the ideal pump flow rate at this head. Certain factors, such as insufficient motor cooling, pump motor life, additional friction loss, and insufficient power supply from the PV system can all lead to pump underperformance, resulting in a lower flow rate at the desired head. Hence, we thought it best to pick a pump whose ideal point of system operation is greater than needed, thus already accounting for underperformance ahead of time and eliminating the element of unwarranted system behavior. In the rare case that the pump chosen will actually perform at the indicated flow rate, the community will benefit because the water will be pumped in a smaller amount of time, leaving any remaining electricity produced in the daylight hours for other uses, such as storage or connection to another power sink.

An identical procedure was carried out in selecting the booster pumps for tanks one and three. The summary of all the pumps chosen for the system are outlined below in Table 14 on page 45. The table also includes the total number of PV modules that is needed to power each individual pump. A Franklin V6 Vertical – 7.5 hp (5.625 kW), 50 GPM booster pump was chosen for tank one. Its rated flow rate is 50 GPM; based on the system – pump performance curve, the optimum point of operation was found to be 50 GPM at 400 feet of TDH. The desired flow rate is 30 GPM, which should produce approximately 340 feet of TDH. Once again considering the possibility of pump underperformance, this pump was decided to be a fit despite the fact that its GPM was found to be slightly higher than needed at the system TDH. The system – pump performance curve for booster pump for tank one can be found on page 125.

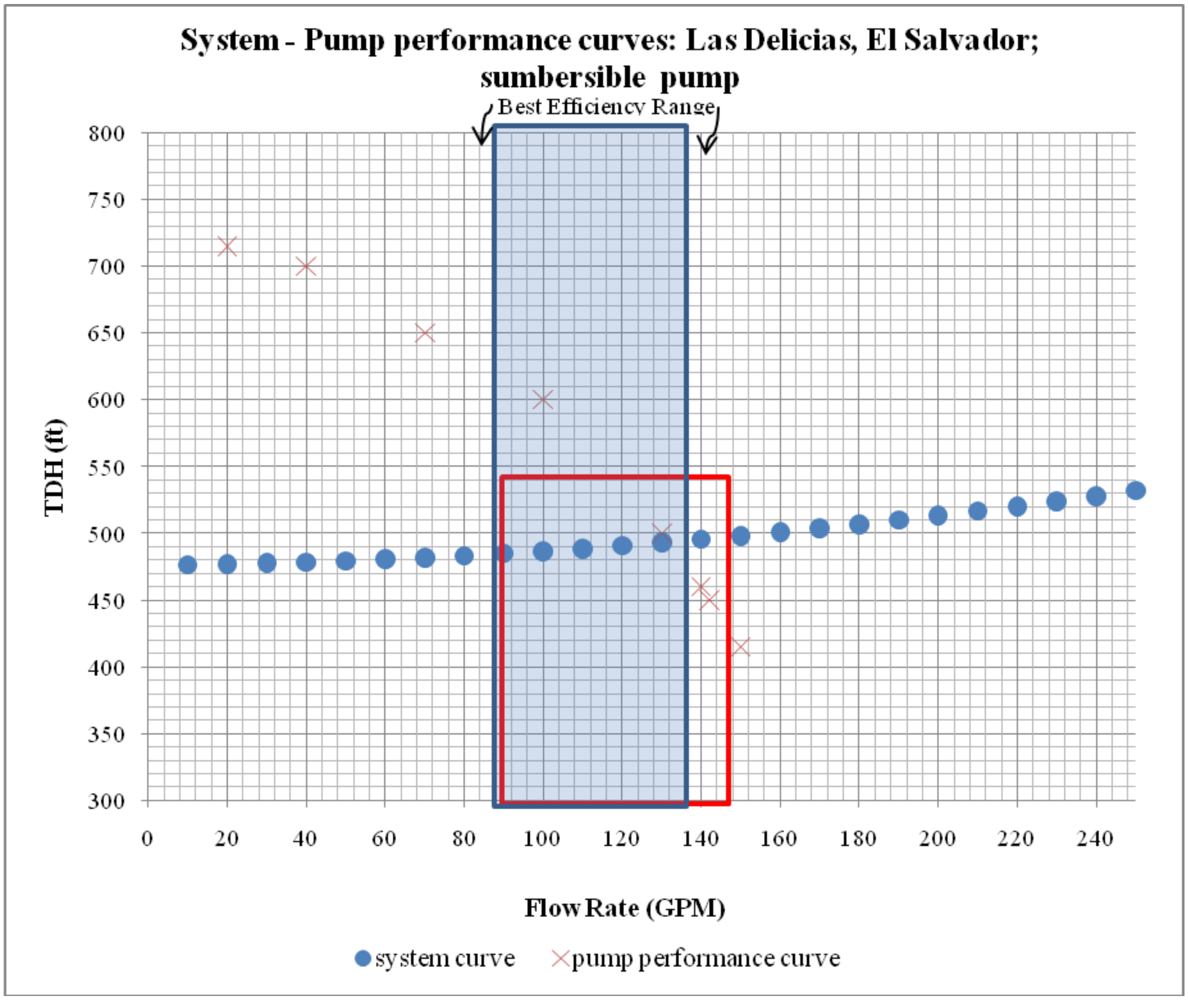


Figure 13. System – pump performance curve for the submersible pump; the pump is Franklin 100SR6-25HP pump with a Franklin 25 hp motor. The desired flow rate falls within the best efficiency range of the pump. The pump also produces enough flow rate and head for the system.

A Franklin BT4 Horizontal (SS) - 1.5 hp (1.125 kW), 25GPM booster pump was chosen for tank 3 was chosen. Its rated flow rate is 25 GPM; based on the system – pump performance curve, the optimum point of operation was found to be at 200 feet at 25 GPM. Our calculations showed that to pump the desired amount of water from the new tank to tank three, the pump must be able to operate at 15 GPM for a TDH of 201 feet. The pump chosen provides more than enough flow rate for the stated TDH. Once again, we were confident in over sizing the pump due to the chance of the pump underperforming under field conditions. The system – pump performance curve for booster pump for tank three can also on page 126.

Table 14. Summary of pumps used for Las Delicias, El Salvador.

Pump	**[HP]**	**[kW]**	**[GPM]**	**Desired GPM at the system TDH**	**TDH [ft]**	**Number of PV modules**
Submersible	25	18.75	125	105	487	19
Booster to tank 1	7.5	5.625	50	30	343	6
Booster to tank 2	1.5	1.125	25	15	201	1
Total	**34**	**25.5**				**26**

Considering the control box

The control box is an essential tool for controlling the motor power. It is responsible for starting and shutting off the pump and maintaining its power throughout the entirety of the pump running. It converts the voltage received from a power source into the voltage required by the pump. There are several options for control boxes, particularly with respect to the starting and shutting off scenario. Most control boxes use the direct-on-line start which applies the full line voltage to the motor. The disadvantage with this method of motor start is that it usually provides the motor with the highest possible starting current, which is often six to seven times higher than needed. As a result, there is a momentary unnecessary spike in voltage at the start. This initial voltage surge can be harmful to the motor and may lessen the motor life [19].

Initial assessment of the Las Delicias, El Salvador water system demonstrated voltage spikes during the starting of the pumps. To eliminate this concern and protect the pump motor life, we looked at two alternative options.

Option one is the Variable Frequency Drive, a type of a starter that controls the amount of voltage the pump motor receives during start and shut off. This mechanism gradually increases the voltage supplied to the motor, thereby reducing any voltage (and thus torque) spikes during start up. The controlled and gradual torque increase translates to less motor wear, prolonging its lifetime. Furthermore, by constantly controlling the voltage supplied to the motor, VFD is able to procure significant energy savings[1]during pump runs [20]. An additional feature of the VFD system is the ability to control the flow rate output (for which purpose we have looked into for the old design system with two pumps in series). VFD mechanism varies the speed of the motor by controlling the power consumption. While this is an interesting feature, it does not apply to the new design in Las Delicias where there are no pumps in series and no variability in demand, with the flow rate set at specific GPM. For more on flow control, please see the next section, *Considering flow control*. One disadvantage with VFD is the high capital cost. Systems have been known to range from $3,000 for 5 hp to over $45,000 for 300 hp [20]. Considering the unnecessary flow control and the intensely high cost, this option was decided against.

In search of better voltage control for the motor, we also looked at a soft starter system. After a detailed evaluation of this mechanism, we have decided to invest in a soft start for the main submersible pump. Figure 15 on page 47 demonstrates the difference in the starting torque between the direct-on-line start and the soft starter. As seen in Figure 15, this mechanism ensures

[1] For a 25 hp pump working for 23 hours a day (2 hours at 100% speed, 8 hours at 75%: 8 hours at 67%; and 5 hours at 50%), energy used has been reduced by 45%.

a gradual increase in torque (and therefore voltage) during startup; the same gradual effect is also seen during shut off. During the start, the gradual increase in the torque (instead of a choppy spike) reduces the motor wear and increases the lifetime of the motor. This type of starter also reduces motor energy losses by continually monitoring the voltage supplied to the motor. During lighter loads, the soft starter reduces the voltage while maintaining the full operating speed, thus saving energy without inducing flow rate losses (as seen with VFD). With the use of a soft starter the initial current is at most four times the normal running current. This gradual starting on and shutting off of the motor also smoothes out the flow of the water, preventing any pressure waves from forming in the pipes. The disadvantage with this starting method is its cost, which, although smaller than VFD system, can still be as much as two times the regular starting method. However, considering that it saves energy, more affordable than VFD, prolongs motor life and guarantees less pump downtime (a very important consideration in a system where the submersible pump is the only method of obtaining well water) we consider this a worthy investment into the system [19, 21, 22].

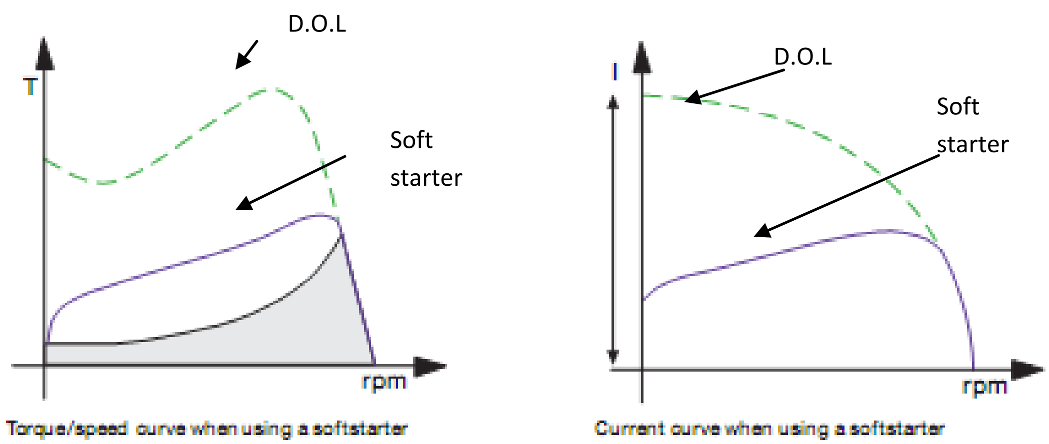


Figure 15. The diagram shows the torque vs. rpm graph. The green dashed line represents the torque –rpm of a direct on line (DOL) starter. There is an initial high torque that increases to a maximum torque before reaching the desired rpm. In comparison, the soft starter starts at a low initial torque and gradually increases the motor to the desired rpm. Note that the initial torque and final torque are much lower with the soft starter than the DOL starter. The same trend is seen in the current-rpm plot. The initial current supplied to the motor by DOL is much higher than needed. The soft starter supplies a low and steady current to the motor.

The soft start was considered for all three pumps, but we decided on investing in just the soft starter for the submersible pump. This was because the submersible pump is the lifeline of the water supply system; if it is down, then the community receives no water. Consequently, it is important to ensure its best possible operation and maintenance. Meanwhile, there is flexibility with the small booster pumps that allows for one to go offline for some time without incurring high water stress on the community. We thought it best to avoid the high cost associated with the soft starters for these pumps.

Considering flow control

There are several types of pump flow controls: manual valve control, orifice plate control, and variable frequency drive (VFD). In determining which flow control method best suits the needs of the system in Las Delicias, simplicity, cost, and societal benefits were all included in the decision process.

As mentioned in the Considering the control box section, VFD is an automatic control system that uses feedback control to control the speed of the pump (and therefore the flow rate) based on demand. It has the dual purpose of controlling the flow rate and the power consumption of the pump. This type of control is best used when the demand is variable and significant energy savings can be obtained by slowing down the pump during periods of less activity. In the Las Delicias water system there are no variations in the pump flow rate. The pump schedule was designed around the sun schedule: the pump works when sun is available (since the PV is the sole power supply to the pump). Hence, to pump the 80,000 gallons needed throughout the day, the pump flow rate is set at around 105 GPM for the submersible pump and 30 GPM and 15 GPM for booster the two booster pumps. Based on our design, the system does not need this type of flow control, and consequently this option was discarded. Because the motor power control was still deemed essential, the soft starter was chosen for that purpose.

Orifice plate control is a form of pre-set flow control. It is a low cost and easy method of measuring and controlling fluid flow. The orifice plate is built into the system and is designed to allow only a specific volume of water through. Its design is such that it is essentially constricts the fluid to a smaller cross sectional area, thus reducing how much fluid may pass per second [23, 24]. Unfortunately this design creates extra pressure drop across the pipe and results in unwanted hydraulic losses. Orifice plates are also subject to problems with erosion, making them lose their accuracy after some time [24, 25]. Thus, this option was also dismissed.

Manual valve control is the flow control that was chosen for this system. It is affordable and easy to implement and does not have unwarranted side effects such as added permanent pressure drop that accompanies orifice plates. There are a variety of valves that may be used for flow control. The butterfly valve is the most economical method to manually control flow. Furthermore, its light weight and design make it easy to open and close quickly with very little force required [23, 24, 25, 26].

In using manual control, the system loses its ability to accurately control the flow and requires the need of an extra employee to work the valves. However, job creation is equal in its advantages to the low cost and simplicity of the system. In a small town like Las Delicias, where jobs are hard to come by, creating even a small paying opportunity such as a valve controller is a great benefit for a family. It provides extra disposable income that may be used for education, health, or recreation. The wellbeing of a community depends on its residents and happier, healthier, and more educated persons are able to more actively participate in community matters and add to the productivity of society as a whole. Though it is difficult to place a value on such issues, there are methods of estimating the economic value in such small opportunity creations. This is covered in more detail in our *Financials* sections.

Considering level control

Level control is another aspect of the control process that is often included in designing a pump process. Like flow control, the water level in a storage tank may be monitored automatically or manually. Automated level control adds cost to the system and unnecessarily complicates the process [27]. Furthermore, the volume of water pumped daily is significantly lower than the total volume of the tanks, eliminating the possibility of overflow (especially because the flow rate will be controlled daily). Manual control is economical and relatively easy to implement. It also creates a small employment opportunity. This responsibility may either be added to those of the pump or the valve controller, or it could be a smaller type of job on its own.

There are several possibilities for manual level control, including a pressure gauge (whose reading can be used to convert to head of water) and a level reader. They are both inexpensive and very easy to implement. We decided to invest in a level reader for the new tank in Las Delicias. The device (a sample is shown in Figure 16) is made out of see-through plastic and easily displays the level of water in the tank.

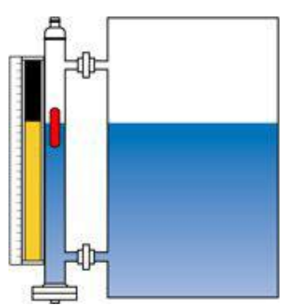


Figure 16. A sample diagram of a level reader. The water from the tank pushes the water in the tube up to match the level in the water tank.

Sourcing the pump

This system required three pumps, one submersible and two small booster pumps. There were two methods of obtaining the pumps: buying them in the US and shipping to El Salvador, or purchasing them directly in El Salvador. After some inquiry into both US based and El Salvador based distributors, we discovered that the price discrepancies are very low, with both estimates being close to $15,000 (personal communication, Sagrisa, March 5th, 2011). From our research, there were no financial benefits of buying pumps in El Salvador instead of in the US. However, we considered this purchase from a different standpoint: the standpoint of the community. For projects in the developing communities such as Las Delicias, it is always recommended to source materials and technology locally [28]. This is because the local craftsmen and technicians are well trained in repairing the equipment they have worked with before rather than something they have never seen. Fortunately, Las Delicias is located close to the capital San Salvador, meaning that there will be plenty of local tradesmen who will know how to repair a pump. It is highly likely that the villagers will be able to find someone to fix a pump that has been sourced elsewhere. In this case then, we decided it does not matter where the pumps come from. For convenience purposes, it might be better for the EWB project team to purchase the pumps in El Salvador so as to eliminate the hassle of shipping the pumps from the US to El Salvador.

Backups

In the rare case of an electrical system failure, the electrical grid will be used as the backup power supply. The electric grid is connected to the AC breaker panel in the same manner as the solar power system and power is likewise routed to the pump and excess loads. The failure of individual PV modules is not a primary concern as the solar power system will still be able to provide electricity through the other modules. Including the combiner box has the benefit of allowing operators to disconnect an individual solar sub-array and repair while all other sub-arrays are still functioning. The electric grid is able to provide sufficient power to the hydraulic system for the short time required to repair or replace the malfunctioning component of the power system. However, the drawback of the electric grid is the relatively high variable costs of electricity.

In the case that a unit has to come offline, having backup equipment is essential in the continued operations of a process. In the El Salvador water supply system, PV modules and pumps are the main units of operation.

While PV modules may be supplemented with the grid or battery power, the pumps are a harder case. There are no alternatives to pumps other than replacement pumps. However, considering that pumps are a major part of the total system cost, buying spare pumps could get very expensive and increase the total investment. Because the money for these types of projects is fundraised from various vendors, minimizing cost is ideal so as to ensure complete project funding. Moreover, there may be security concerns with having spare pumps. There are no security measures in the community and having new, unused pumps in the unsecured pump house could be risky. The pumps may be sold in the nearby capital city San Salvador, or implemented in neighboring towns that lack proper funds for a new pump. Because the pumps used in the Las Delicias system are small and easy to carry, they are considered at risk for being stolen.

There was also the option of buying some spare parts for the pump. However, considering the lack of technical expertise on site, we dismissed this idea and thought that repairs at a professional pump repair shop would be more economical and avoids extra damage that could be caused as a result of improper installation.

Although it is atypical for a process, we have decided that we will not invest in spare pumps for Las Delicias. There is currently a 15 hp pump that may be used as a spare in the case the new 25 hp submersible pump has to come offline. Although the current pump is smaller than the new pump and will have a smaller flow rate, it will still be able to provide some water to the community. There will be no alternatives to the booster pumps. We considered changing the impeller on the current 60 hp booster pump, installing a smaller impeller for smaller flow and thus less power usage. However, we could not determine the make or the model number of the booster pump and had to dismiss this option. Furthermore, we discovered at the end of March that the 60 hp booster pump broke and is most likely beyond repair. As of today, it cannot be considered as a backup pump. Hence, the two booster pumps are without backups. However, considering that the town is close to San Salvador, and based on the estimates made by EWB (after speaking with town representatives), we have determined that should the booster pumps break, the time to fix it should not take longer than one week. In the case that it cannot be fixed, there are numerous suppliers in the capital that may be able to provide and install a pump within a span of a few days. Considering that the community will no longer pay for electricity (or at least greatly reduce their grid usage), there should be money in the community “money pot” for the maintenance or purchasing of a pump. Although it is not the best option, it is the best one for the system considering the financial constraints in place.

Power system

Many alternative power sources were considered but the ultimate economically and practically motivated choice for the alternative energy system in Las Delicias, El Salvador was a traditional photovoltaic system. The system includes enough solar panels required to supply the 25.5 kW of electrical energy needed for all three water pumps. The solar power system also includes a combiner, a solar controller, an inverter, batteries, a battery bank, a panel breaker, and cables (for a full design flow diagram, please see Figure 17 on page 55). The power system was designed to provide water to the three tanks in the village in a scheduled manner that should anticipate and fulfill all water needs. Three different scenarios were considered to determine the optimal number of hours for the water pump to be operating. Please see the Appendix, *Calculations* section for calculations of all three scenarios, and *Tables and Figures* for the final results of all three scenarios (presented in Table A9 on page 130). It was determined that it is optimal to pump for 12.6 hours throughout the day, starting with the rising of the sun at 6 am. Also, to ensure the system was capable of functioning during the times of the year with the least amount of sun, calculations were based on the month of October, the month with the least solar insolation at any time of the day [29] (please see Table A10 and Figure A11 on page 131 for insulation data for Las Delicias, El Salvador). All other months of the year have increased insolation and are ensured to provide more than the necessary power to run the pumps. The data used for power calculations is based on data collected by NASA over a 22 year span; the data points are assumed to be reliable for the purposes of this project.

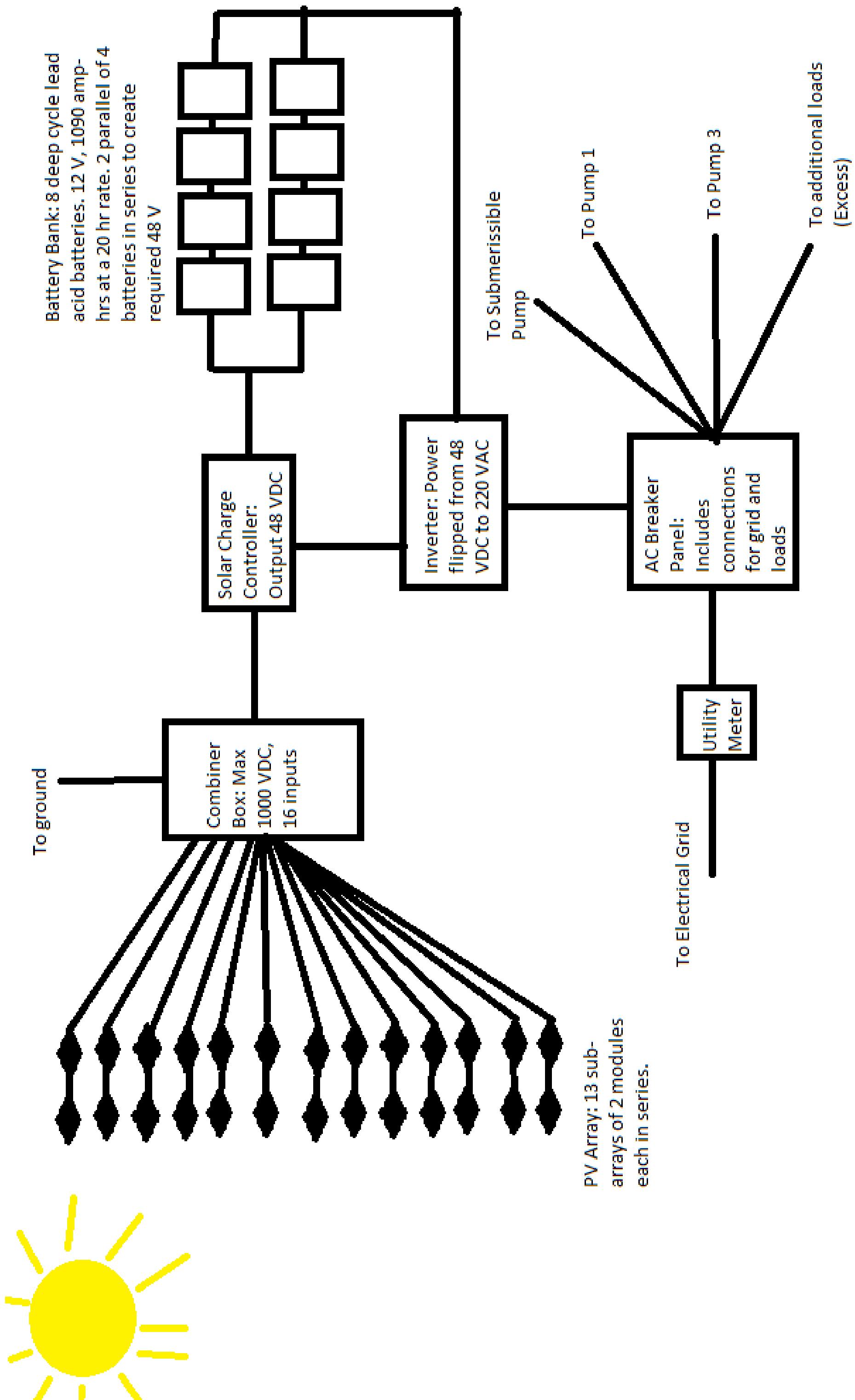


Figure 17. Process flow diagram of the Photovoltaic power system in Las Delicias, El Salvador. All components are included and electrical wires connect the system together.

Solar Panels

The solar panels were chosen to minimize cost and required area. Best Sun New Energy Co., Ltd was chosen as the supplier for the solar panels as they are the most affordable and most reliable supplier based on customer reviews. Monocrystalline silicon solar cells were chosen on the basis of price as they are able to provide the most power for the least number of panels. Each module consists of an array of 72 (6 by 12) 190 watt solar panels operating at 17.75% efficiency. Table A12 on page 132 provides alternative solar panels considered, including their operating efficiencies.

The modules selected operate with a maximum power voltage of 36.36 volts and current of 4.95 amperes. Each cell area is 125 mm x 125 mm and then entire module has dimensions of 1580 x 808 x 46 mm. Each module is made of an aluminum frame contributing to the total weight of 16 kg. The surface maximum weight capacity is 200 kg/m^2 (usually this is a concern in snowy areas where snow can accumulate on the solar panels), quite sufficient for any forms of fallen debris. This rating of 180 watts power is based on measurements at Standard Test Conditions (STC) of 1.5 AM, 1000 W/m^2 and 25°C [30]. The conditions in Las Delicias are not at STC, the most deviant of which being the insolation of 100 W/m^2 (see Figure A11 on page 131). Throughout different times of the day, as the sun changes position in the sky, the insolation incident on a horizontal surface varies. The minimum number of solar modules needed was calculated based on the minimum insolation incident on a horizontal surface in the least sunny month of October. In this manner, the solar panels considered will provide adequate power to run pumps during all times of the day, any time of the year. However, this increases the wasted energy as during sunnier months and hours the panels will provide excess energy. However, this excess power cannot be sold back to the grid. The month of October has an average insolation incident to a horizontal surface of 0.54 kW/m^2 from 9 am – 12 pm, 0.75 kW/m^2 from 12 – 3 pm, and 0.41 kW/m^2 from 3-6pm. From equations one through three, which are referenced on page 150 and 151 in the Appendix, it was calculated that during the dimmest hours of 3 – 6 pm, 26 modules are needed to power a system of pumps requiring 25.5 kW. These 26 solar panels will require an area of 33 m^2 and will be situated on the land near the pump house as that area is not used for agriculture. The tolerable temperature range for the PV cells is -40°C to 85°C, within the range of operating conditions. Each module has an open circuit voltage of 37VDC and short circuit current of 5.5A. The panels will be connected in 13 parallel sub-arrays of two modules each. The voltage in series will sum to 74VDC and the 13 sub-arrays will be combined in parallel through the use of a combiner. The 26 modules weigh a total of 416 kg and need to be shipped to El Salvador at an additional cost. Throughout the nine hours of sunlight each day these panels provide a total 325 kWh of energy, calculated from equation four. During the nine hours of sunlight the solar modules provide the energy required to run the pumps (230 kWh) while simultaneously charging batteries. An additional 3.6 hours of pumping (92 kWh) at night is required to fulfill all water needs and is supplied by the energy stored in the batteries. For this, a batter bank consisting of eight batteries is needed.

Combiner

For the system in Las Delicias, one large combiner boxes is needed as the array consists of 13 sub-arrays of two modules in series. The largest combiners commercially available have maximum volts direct current (VDC) of 1000 volts and are able to connect a maximum of 16 inputs [31]. Beijing Multifit Electrical Technology Co., Ltd. was chosen as the provider for the combiner box based on price and quality. They provide a two year warranty and offer the competitive price of $200 for the entire combiner box.

Charge Controller

The solar charge controller will be sourced from Best Sun New Energy Co., Ltd.; they are able to provide a MTTP charge controller that has a current range of ten to 60 amperes. This company also provides 12, 24, or 48 volts of voltage on an automatic basis. We will operate the system at 48 volts as the input voltage is high (~75 VDC) and the least amount of voltage change will maximize the efficiency. The cost for the controller is included in the BOS cost estimation as $0.65/W.

Batteries

Approximately 92 kWh of energy must be stored in batteries for night usage. This represents a significant amount of energy storage at very particular design specifications. Crown Battery provides deep cycle batteries of sufficient voltage (12V) and the most storage available at 1090 ampere-hours at a 20 hour rate, the Crown 12-125-13. The 20 hour rate is important as the solar panel system is expected to charge and discharge every day over a period of 12.6 hours. In addition to the favorable technical specifications, the warranty of 1500 cycles to 80% depth of discharge for five years full replacement and the price of $3,200 are competitive within the market [32]. The system requires eight of these batteries to be contained within a battery bank to shield the batteries from the elements. The batteries will be connected in a dual configuration with two parallel series of four each so the total voltage is 48 VDC. Enclosures are typically made out of steel or aluminum and cost approximately $300. Another concern regarding the battery bank is the shipping of these industrial sized batteries weighing 385kg each totaling 3085 kg.

Inverter

The inverter cost is included in the BOS estimate as $500; note, that it requires replacement every ten years.

AC Breaker Panel

The breaker box will be sourced from New England Solar Electric, Inc. at a cost of $169. The box consists of one 2-pole main breaker and six circuit breakers, more than is needed for the solar power system.

Apatut, the Philippines

The residents of Apatut currently have no access to clean water. There is no water supply system in place and, based on government estimates, a federally sponsored system will not be built for at least another ten years (personal correspondence, EWB-MAP, January 18, 2011). It is essential to design a grass roots water system that will enable Apatut's residents to obtain clean drinking water. The EWB team in charge of this project has designed a system that places a 20,000 gallon tank atop a 180 foot hill above the community. Figure 18 shows the system design. The pump is submersible and pumps water to the tank at the top of the hill. Considering our lack of detailed knowledge of the surrounding area and the simplicity of this design given the size of the village, we thought that this was an acceptable design and chose not to amend it. Instead, we focused on developing an alternative to grid, which is known to be expensive and unreliable.

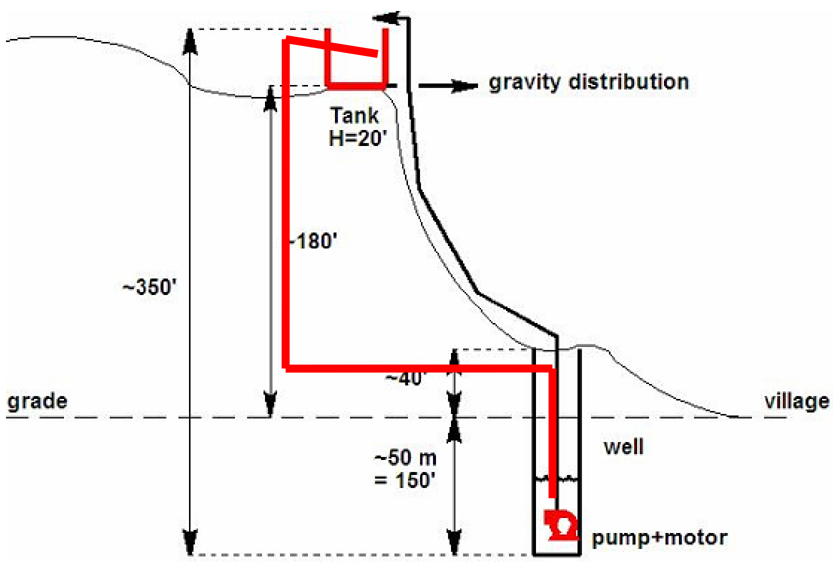


Figure 18. Apatut, the Philippines hydraulic system design.

Selecting a flow rate

The inhabitants of Apatut require 30 gal/person/day and with 750 residents, that equates to 22,500 gal/day for the entire village. Scenario one was determined in the same manner as for El Salvador; 42 GPM are required from the pump, needing 5.6 kW of power (see Table A13 on page 133). For the 22 hours of pumping in Scenario two, 17 GPM are required, demanding two kW of power (see Table A14 on page 134). When trying to utilize the same iterative solution, the excess energy provided by the eight solar modules required in Scenario one (55 kWh/day) provides more than 13 hours of extra pumping, more than the 22 pumping hours upper limit. Scenario one was chosen for the pump schedule as it eliminates the need for batteries without increasing the cost of the PV modules significantly (See Table A15 on page 135).

Selecting a pump

The method of selecting an appropriately sized pump was outlined in the section on Las Delicias, under *Selecting a pump*. The procedure is identical to the one described in that section. To determine TDH, only static height and head loss were accounted for, applying the same assumption that the pump will be completely submersible and the water will not need static lift. In calculating TDH, the pipeline was approximated as four sections: drop pipe, horizontal section 1, vertical section 2, and the final small horizontal section 3. The full table of TDH for all the components and the entire system can be found on pages 136 to 140 (Figures A16 through A20)

Several pumps were evaluated for the Apatut water system. Given the desired flow rate of 40 GPM, the TDH calculations determined that a pump of at least 5 hp (3.75 kW) will be needed. We considered a 5 hp and a 7.5 hp (5.625 kW) and settled on obtaining a 7.5 hp pump. Again, our reasons for over estimating the pump power is due to the possibility of pump underperformance in the field conditions. The pump chosen is the Aermotor A50+ Series, with a Franklin motor. The pump performance curve intersects the system curve at 300 feet and 62 GPM. Since we are assuming that this is an overestimate, we decided that this pump will fit our system and expect flow rates under field conditions to be close to the actual desired flow rates of 40 GPM.

Considering the control box

The submersible pump is the only pump used in the Apatut water system. Since the village is located far away from any major city where pump repair shops are located, and because this is a first system of its type in this village, we decided that investing in motor protector system, Pumptec-Plus. Pumptec-Plus protects all Franklin single phase motors from problems that may arise due to low water level in a well, low voltage supplied to the motor, worn out pump parts, and faulty check valves. Its application extends motor life, an important consideration for this system. Moreover, we thought this essential because of its feature to sense water level in the well, which will otherwise be unknown and has the potential to cause pump dry running (if the water table is not replenished enough to keep the pump submerged).

We also considered using a reduced voltage starter, such as a soft starter in the Las Delicias system, but through our research, we discovered that using these types of starters is unacceptable with single phase motors. Consequently, an investment into Pumptec is essential because it is one of the few methods of motor protection available for single phase motors.

Considering flow control

The submersible pump pumps the water directly to the 20,000 gallon holding tank that then distributes the water by gravity. The tank holds most of the water for the entire community's daily water needs. Having a flow rate larger than the one needed will result in filling the tank faster than expected, leaving the village the ability to use the PV modules for purposes other than powering the pump. Since we oversized the pump for this system, we do not expect flow rates lower than the desired 30-40 GPM range. Considering both the cases of too much and too little flow rate then, we decided that there is not significant need for flow control in this system. However, as a standard procedure, we included a butterfly valve for flow control. This type of valve is easy to use and inexpensive to implement and therefore fits the needs of this developing community.

Sizing the New Tank

There is currently no tank in place in Apatut, but the EWB-MAP project team has designed a tank of roughly 28,000 gallons. The dimensions of the current tank are 22x22x8 feet. In a scenario similar to the one we described with Las Delicias we tried to minimize costs by finding an optimal tank volume. The village requirements are 30 gallons of water a day per person. With this we estimated that the pumps must be able to pump a total of 22,250 gallons of water a day (assuming a population of 750 [33]). In the optimal scenario, scenario one, the pump will work for nine hours each day, pumping at the GPMs specified previously. To start with some water in the tank, we designed the system to pump for 2,500 gallons for roughly an hour the day before, as to avoid the tank from ever being empty.

Each day the tank starts with 2,500 gallons, and the water is withdrawn and input simultaneously by water end users and the pump, respectively. At some point of the day, the amount withdrawn is at a minimum. When this occurs the tank is at its maximum volume of the day. This number was tabulated from finding the difference between gallons accumulated and gallons withdrawn. For Apatut we determined this maximum volume to be 9,925 gallons. This value tells us that the tank size must hold at least 9,925 gallons. Therefore, when sizing our tanks we decided to create a slightly larger tank to avoid possible problems with overflow. This meant that we would obtain a tank of roughly 20,000 gallons.

Our final decision with regards to tanks was to determine the shape of the tank. Table 19 summaries the typical dimensions of a 20,000-gallon cylindrical tank, while Table 20 summarizes the typical dimensions of a square tank. The EWB chose a square tank as part of their original design, however this was eliminated in our system for several reasons. Cylindrical tanks were chosen because their shape minimizes the stress on a tank because stress is evenly distributed over the walls of tanks, which makes these tanks more durable. Furthermore, cylindrical tanks require less material to build and are thus more affordable. This is a different and perhaps better option than the rectangular tank recommended by the EWB. Discussion of tank shape is detailed in a later section of the report under Rainwater Harvesting.

Table 19. Geometry of Cylindrical tank

GEOMETRY	
Tank Material Type	Ferrocement
Nominal Inside Diameter	18.46 feet
Nominal Sidewall Height	10.00 feet
Deck Slope	1" rise to 12" run
Bottom Slop	Flat
Nominal Capacity	20,025 gallons
Usable Capacity	19,024 gallons

Table 20. Geometry of Rectangular Tank

GEOMETRY	
Tank Material Type	Ferrocement
Base area	22 x 22 ft^2
Nominal Sidewall Height	10.00 feet
Nominal Capacity	28,964 gallons
Usable Capacity	24,040 gallons

Considering level control

The 20,000 gallon holding tank is the only tank in the community. It holds most of the water for the entire community for one day. In the previous section, *Sizing the new tank*, we discussed how the tank is oversized because we do not anticipate storing all of the water for the community, and instead pump the water simultaneously as the water is being used. Thus, we do not anticipate overflow of the tank. However, in the case that some days the water use is very low or the pump provides a larger than expected flow rate, we decided to consider a level control for the system. We looked at several level control options. Our methodology was similar to the one used in Las Delicias: we looked at the simplicity and cost of the level control. Once again, automated level control is expensive and unnecessarily complicated. In the case the system breaks, it will be difficult to fix it in a timely manner (given the village's remoteness). Hence, we opted for manual level control, which is easy to use and inexpensive to implement. We decided to use the same level control system as in Las Delicias, the level reader. Its cost and simplicity are unmatched by any other level controls investigated and therefore we thought it an appropriate technology to use.

Sourcing the pumps

We looked into several sources of pumps, motors and control boxes. There are a variety of distributors within the US that supply a wide range of pumps. The pumps we were looking at ranged in prices from $2,000 for the entire system to $4,000 for the system (which includes pump, motor and control box). The issue with purchasing the pump in the US is that there will be extra costs associated with shipping. Our estimates indicate at least an additional $1,000 for shipping costs is required for the pump and its parts from the US to the Philippines. Because we want to minimize the system cost, we decided to investigate other options that could source the pumps locally and save on shipping costs. An additional reason for local distributors is the consideration of future maintenance and replacement. Sourcing a pump and its parts locally is convenient for the community in the case that any of the pump parts break and must be replaced. It could be expensive and troublesome to find the same parts from a supplier in the US. Pumps that are sourced locally will be easier to repair or replace since their parts are easily accessible to the end users.

We found a few distributors within the Philippines but had trouble contacting some of them. One vendor supplied a price estimate for the pump, motor and control box. Amici Water Systems is a pump vendor based out of the Philippines. It has several locations across the islands, including one in Pomanga, which is located within 150 miles of Apatut. After speaking with the sales representative of Amici, we were given a quote of $1,700 for a 5 hp system. The company did not reply to our inquiry of increasing the pump size to 7.5 hp, but based on the difference in pump prices between the two models in the US, we estimate that the system will not cost more than $2,300. For the implementation of the project, we would recommend researching a few more vendors and comparing their prices. Although the differences in price between the US and the Philippines are small, with at most $1,000 greater in the US, we decided that sourcing the pump in the Philippines is the better option because of the convenience it creates for the community to repair and replace the pump in the future.

Backups

The question of back-up pumps is a difficult one in the Apatut system. As was the case with Las Delicias, pumps make up a large portion of the system cost. Furthermore, we are concerned with security of the brand new spare pumps that are unconnected to anything and are at risk for being carried off easily. Despite these concerns we decided to invest in a back-up submersible pump for the Apatut system. Because of the remoteness of the village and the lack of technical expertise that would enable pump repair, we decided that the back-up pump is a worthwhile investment. The pump used is small, only 7.5 hp. The price estimate from local suppliers was approximately $2,000, including the motor and the control box. Although it is a significant cost, it is fairly reasonable and will not immensely increase the total system cost. As a preventative measure against theft, we decided to hire a watchman, who will also double as a security guard for the PV modules. The pump will most likely be stored at the pump house, although that decision is ultimately up to the community.

Power System

We examined several power source alternative to the grid, but the ultimate choice rested in the photovoltaic system, which proved to be the most economical and practical option for the town of Apatut, the Philippines. The power system provides enough PV solar panels required to supply the 5.6 kW of electrical energy needed for the submersible pump that pumps water for the village. The solar power system also includes a combiner, a solar controller, an inverter, a panel breaker, and cables (Figure 21 on page 68). The power system was designed to provide water to the tank in a scheduled manner that should anticipate and fulfill all community water needs. It was determined (see Table 3 on page 22) that it is optimal to pump during sunlight hours, which span 9 hours throughout the day. To ensure the system is capable of functioning during the times of the year with the least amount of sun, calculations were based on the month of January, which is the month with the least solar insolation at any time of the day (see Table A10 on page 131). The choices for supplier and technical capabilities are the same as those for Las Delicias, El Salvador because of the similarity in the project design and objectives. The major deviations from the system design in El Salvador are the size and quantity of the equipment needed for Apatut as its requirements are on a much smaller scale.

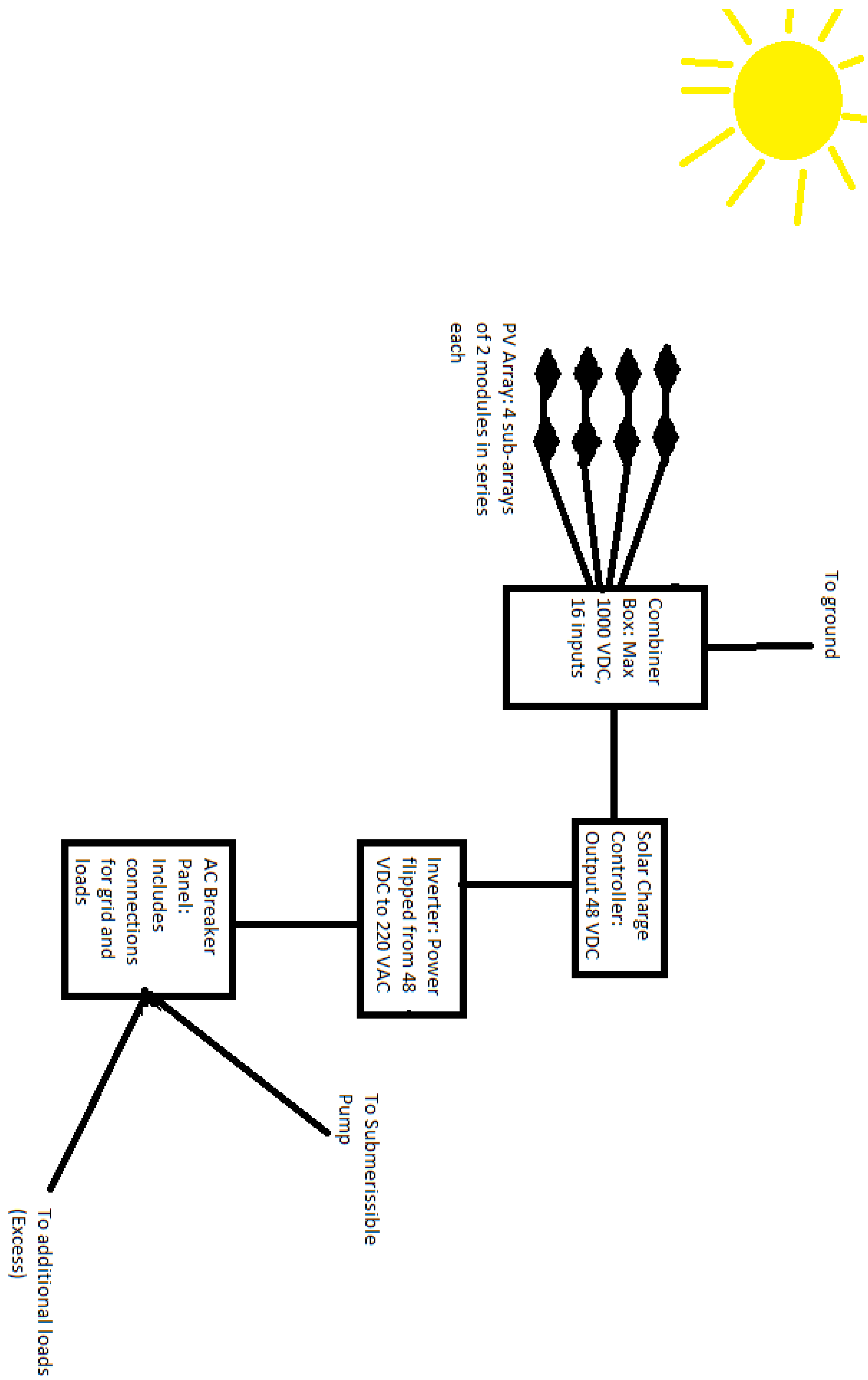


Figure 11. Process flow diagram of the Photovoltaic Power System in Apatut, the Philippines. All components are included and electrical wires connect the system together.

Solar Panels

The minimum number of solar modules needed was calculated based on the minimum insolation incident on a horizontal surface in the least sunny month of January. In this manner, the solar panels will provide an adequate amount of power to run the pump during all times of the day any time of the year. However, this does increase wasted energy since during sunnier months and hours the panels will provide excess energy. The month of January has an average insolation incident to a horizontal surface of 0.22 kW/m^2 from 9am-12pm, 0.70 kW/m^2 from 12-3pm, and 0.64 kW/m^2 from 3-6pm. From equations 1 and 2 (Table A22 and Figure A23 in the Appendix pages 141 and 142) it was calculated that during the least sunny hours of 9am-12pm, 8 modules are needed. The 8 solar panels will require an area of 10 m^2 and will be situated on the land near the pump house as that area is not used for agriculture and will also reduce the length of wire required to connect to the submersible pump. Throughout the 9 hours of sunlight each day these panels produce 91 kWh of energy; however, only 36 kWh are used by the pumps during these 9 hours and 55 kWh are unused excess energy that to power other loads in parallel. For future projects, a battery bank for storage should be considered.

Combiner

For the system in Apatut, one large combiner box is needed since the array consists of 4 subarrays with 2 modules in series. Beijing Multifit Electrical Technology Co., Ltd. was chosen as the provider for the combiner box based on price and quality. They provide a two year warranty and offer the competitive price of $200 for the entire combiner box. See the appendix for calculations for all 3 scenarios presented in Pump Scheduling.

Charge Controller

The solar charge controller will be sourced from Best Sun New Energy Co., Ltd.; they are able to provide a MTTP charge controller that has a current range of ten to 60 amperes. This company also provides 12, 24, or 48 volts of voltage on an automatic basis. We will operate the system at 48 volts as the input voltage is high (~75 VDC) and the least amount of voltage change will maximize the efficiency. The cost for the controller is included in the BOS cost estimation as \$0.65/W.

Inverter

The inverter cost is included in the BOS estimate as \$500; note, that it requires replacement every ten years.

AC Breaker Panel

The breaker box will be sourced from New England Solar Electric, Inc. at a cost of \$169. The box consists of one 2-pole main breaker and six circuit breakers, more than is needed for the solar power system.

FINANCIAL CALCULATIONS

The unique nature of this project forced the design group to focus special attention on minimizing the costs of the power and hydraulic system in both Apatut, the Philippines and Las Delicias, El Salvador. The primary concern of the system is to provide the most basic and important need of clean water to undeveloped, agricultural villages currently lacking the infrastructure as opposed to maximizing the net present value and generating maximum profits from investment. Investment in this project is not dependent on the internal rate of return calculated from cash flows but rather on the philanthropic and altruistic nature of charities, organizations, and charitable individuals. An alternative manner of considering a social project such as these is from the point of view of the government. The government can be envisioned as an investor which invests in socially profitable projects. In this way, the productivity gain can be translated directly to tax revenues and are applicable in calculating the Net Present Value and Internal Rate of Return for each project. As the government is faced with a variety of social projects each year and must choose between them, the most appropriate discount rate to use is cost of capital of the government, or their cost of debt. This equates to the calculations done by most investors as they apply the required discount rate of their investment firm (the government for these projects) to the future cash flows of the project (productivity gain as a proxy for tax revenues).

Revenue Assumptions

It was essential to consider the increased productivity possible with the new system. Under the current systems, the villagers must either use water collected throughout the week, or find other sources of water. Both options cause decreases in productivity due to the related opportunity. If water is stored for long periods of time without filtration or purification, it is highly likely that parasites and bacteria will inhabit the water and cause illness. The Central

Intelligence Agency rates the risk of water-born infectious diseases in both El Salvador and the Philippines as high [34]. To avoid this risk, villagers can venture out to find other sources of fresh water, such as mountain springs. Although this will decrease the probability of contracting a debilitating water-borne illness, it does detract from productivity by requiring time. Villagers spend time collecting and purifying water rather than engaging in wage earning labor.

Cost Assumptions

The cost assumptions primarily consist of initial investment costs in the power and hydraulic system. For the power system most major components, including panels, charge controller, and inverter are being sourced from Best Sun New Energy Co., Ltd. Using a brochure provided (see Figure A21 on page 141) a $/Watt estimate for both villages was calculated given the $0.69/W cost of a 20,000 W maximum power system and economies of scale. This does not include the costs of the combiner, batteries, and the AC breaker panel (accounted for independently). The combiner box is estimated to cost $200 from the Beijing Multifit Electrical Technology Co., Ltd and the AC breaker panel is estimated to cost $169 from the New England Solar Electric, Inc. The warranty on the entire system provided by Best Sun is five years, but for the individual solar panels it is 25 years. Replacement for the combiner, breaker panel, and controller is negligible but the inverter can be expected to need replacement every 10 years. The eight industrial sized deep cycle lead acid batteries also represent a significant cost to the system. Crown Battery in Ohio will provide the batteries for $3,200 each for a total cost of $25,000. The warranty is for five years or 1500 cycles. We assumed a useful life of 10 years given the inclusion of the aluminum battery bank and the charge controller minimizing the possibility of overcharge. Instillation and other labor costs for implementing the system must also be considered. The US Department of Energy, Energy Efficiency and Renewable Energy division provide estimates for the instillation costs at $0.17/W of the system and other/indirect costs of

$0.76/W. The other/indirect costs include "design, engineering, site-related costs, permitting, and profit", but as the tasks of design and engineering are completed, this cost was revised down to $0.38/W or half the original.

Las Delicias, El Salvador

Currently the revenues to the water system of Las Delicias are based on a rudimentary collection method with little financial infrastructure. According to EWB representatives, each family pays $5 per month to cover for all the costs related to the water system and approximately 10% of the families fail to pay. From Figures A24 and A25 on pages 143 and 144, it was determined that and amount of $27,000 is collected annually. The assumption of a 1% increase in productivity is appropriate to account for the difference in system design. Currently villagers are only able to collect water twice a week, Tuesday and Thursday mornings and must find other sources of water at other times. From assumptions presented in Table 16 in the Appendix, the annual opportunity gain provided by the increase in productivity is calculated. A $/Watt estimate of $0.65 was calculated given the $0.69/W cost of a 20,000 W maximum power system and economies of scale (the power system required is 63,000 W maximum power).

Using a discount rate of 1.6%, the Net Present Value (NPV) of the combined solar power system and the new hydraulic system was calculated to be $413,000 (Figure A26 on page 145). Moody's, a credit rating agency, rates the credit of El Salvador sovereign debt as Ba1. This credit rating determines the required rate of return for public government investments. The typical expected return on debt rated Ba1 by Moody's is 1.6%, which is used as the discount rate applied to cash flows of the project [35, 36]. The internal rate of return based on past payments made by the village was calculated to be 36%, out-stripping most commercial investments. The relatively high IRR and NPV are the result of the inclusion of the productivity gain experienced through access to clean water on a continuous, reliable basis. A 1% productivity increase is assumed (see Table A27 on page 146 for a summary of revenues and costs. Also, see Figures A24 and A25 on pages 143 and 144 for current electric bills and maintenance costs for the water system in Las Delicias). The nature of solar energy decreases the recurring variable costs of inputs significantly as solar energy is free, unlike electricity from the grid. The total investment of the project will be $120,000 with annual operation and maintenance costs of $10,000, the majority of which is made up by salaries for employees.

Another method for considering the financial benefits of implementing this design is to determine the savings afforded the people in the village if the investor were to require no return on investment, merely recuperation of the initial investment. Under this metric, the system could reduce payments needed from inhabitants by 15% in the first year of operation increasing to 21% over 20 years. All materials and labor costs are estimated based on local costs and sourced from local suppliers to ensure accuracy in determining costs. Within the solar power system, the bank of eight batteries constituted for a majority of the investment cost ($25,000). The hydraulic system included investment costs for the new 20,000 gallon tank ($17,000) and the three new pumps ($15,000). Replacement of the pumps is also a significant factor as they must be replaced every eight years[2]. The relevant assumptions are provided in the appendix on page 145, along with annual financial revenues and costs. Although the solar system represents a large majority of the initial investment costs (85%), after initial instillation the recurring costs related to the solar system are miniscule in comparison to the costs associated with maintaining the hydraulic system.

[2] Typical lifespan of pumps is 10-15 years. However, because there will be limited technical knowledge on site, continual use of the pumps for 13 hours a day, every day, and because we are unsure of the sediment content in the water, we decided to estimate a conservative lifespan of the pumps.

Apatut, The Philippines

Currently there is no water system installed in Apatut. It was thus essential to consider the increased productivity possible with the new system. The assumption of a 2% increase in productivity is appropriate to account for this dramatic difference in system design (Figure A28). A $/Watt estimate of the $0.69/W cost of a 20,000 W maximum power system is used (Figure A21 under *Tables and Figures* in the Appendix page 143).

Using a discount rate of 1.6% the net present value of both the solar power system, and the new hydraulic system of was calculated to be $78,000 was calculated (from Figure A29 under *Tables and Figures* in the Appendix page 148). Moody's rates the credit of the Philippines sovereign debt as Ba3. The typical expected return on debt rated Ba3 by Moody's is 1.6%, which is used as the discount rate applied to cash flows of the project [35, 36]. Alternatively, if no rate of return was required and the villagers simply had to pay for the project and all costs throughout the active life, they would be required to pay $500 monthly, less than $4 a family. The internal rate of return based on past payments made by the village was calculated to be 41%, out-striping most commercial investments. A much larger portion of the initial investment is required by the solar power system than the new hydraulic system, however, in subsequent years after investment, operating and maintaining the solar system is much cheaper than the hydraulic system. The relatively high IRR and NPV are the result of the inclusion of the productivity gain experienced through access to clean water on a continuous, reliable basis. A 2% productivity increase is assumed. Also, the nature of solar energy decreases the recurring variable costs of inputs significantly as solar energy is free, unlike electricity from the grid. The total investment of the project will be $22,000 with annual operation and maintenance costs of $4,000 the majority of which are made up by employee salaries. All materials and labor costs are estimated based on local costs and local suppliers; this was done to ensure the most accuracy in determining costs. Within the solar power system, the solar modules accounted for a majority of the costs ($5,500). The hydraulic system included investment costs for the new pump ($7,500). The relevant assumptions are provided in the appendix along with annual financial revenues and costs.

ALTERNATIVE ANALYSIS

Power Options

The main scope of this project was to provide a cheaper method of powering the water pumps in the villages of Apatut and Las Delicias. The project statement emphasized the use of solar power. We looked at various solar power options, and also considered alternatives other than solar power, all of which are described later in this section. Due to various reasons outlined below, including economics and feasibility, we decided to focus on PV technology. However, it is important to outline our reasons behind the dismal of the other available technologies.

Concentrated Solar Power

Concentrated Solar Power (CSP) technologies are often built on a large scale that is not applicable to individual domestic systems. CSP technologies remain attractive because they provide clean power, high reliability, and they are dispatchable. The key advantage to concentrating solar power technologies is derived from the higher thermal efficiencies that are acquired by concentrating energy yield from a larger surface area of collectors. In almost all cases, CSP plants produce electricity using thermal energy to power a turbine via a Rankine cycle. The power flux is reflected and concentrated on an absorber that captures it as thermal energy. A prime mover fluid, such as pressurized water or compressed air, is then heated up using the concentrated energy and the fluid's expansion drives the turbo-generating unit making electricity [37]. While the basic theory behind CSP technologies is common for all CSP systems, there are several designs that can accommodate different economic and environmental needs. The most commonly used ones are divided into three categories: central receiver systems (power towers), parabolic troughs and dish engine systems. This section is dedicated to discussing the three main CSP technologies considered for this project. Table 22 on page 80 summarizes the three different CSP technologies.

Table 22. Summary of CSP Technologies [37].

CSP Technology	Concentration Ratio	Tracking Requirement	Operating Temp °C	Solar-electric efficiency	Unit Size Range
Power Tower	500 – 1000	2-axis heliostats	400 – 600	12 – 18 %	30 – 200 MW
Parabolic Troughs	10 – 100	1-axis reflector	100 – 400	8 – 12 %	30 – 100 MW
Dish Engines	600 – 3000	2-axis	600 – 1500	15 – 30%	5 – 50 kW

Power Tower

A power tower is a central receiver system that consists of a field of mirrors or heliostats that are arranged around a central receiver (see Figure 23). These receivers intercept and direct sunlight from all angles towards the receiver that contains a high-temperature working fluid. Fluids such as a molten salt mixture can be pumped through the receiver and stored for several hours at temperatures ranging from 500-600˚C. A steam Rankine cycle is then used to generate electricity with the working fluid that provides sufficient energy to vaporize and superheat steam before expansion in a turbogenerator. A mixture of potassium and nitrate salts has been proved to be more efficient as thermal storage above 500˚C could be achieved with reduced pressure. This type of slats could also permit continuous dispatchable storage for period of 24 hours or more. The main drawback of such central receiver systems is their high building and operating costs that even in large and scaled-up plants will reach $3000-$4000/kW [37]. In addition to the high costs associated with this type of solar power, there are several other factors that helped us eliminate this option. Power tower CSP technologies are costly, especially compared with other CSPs such as parabolic troughs, solar dish engines and photovoltaics. Furthermore, these technologies are suitable for plants and operations that require large amounts of power. A typical power tower can generate an equivalent of 30 to 200 MW of power. For systems which require less than 30 kW of power such as Las Delicias and Apatut, such technology is not feasible. Power towers also require a great amount of land usage for the placement of mirrors, which is not practical for small-scale projects such as ours. Finally, the use of a Rankine cycle requires expensive and complex equipment such as turbines and compressors, which unnecessarily complicate the system design and require heavy investment and maintenance costs, as well as immense technical expertise to maintain (which neither project sites can provide).

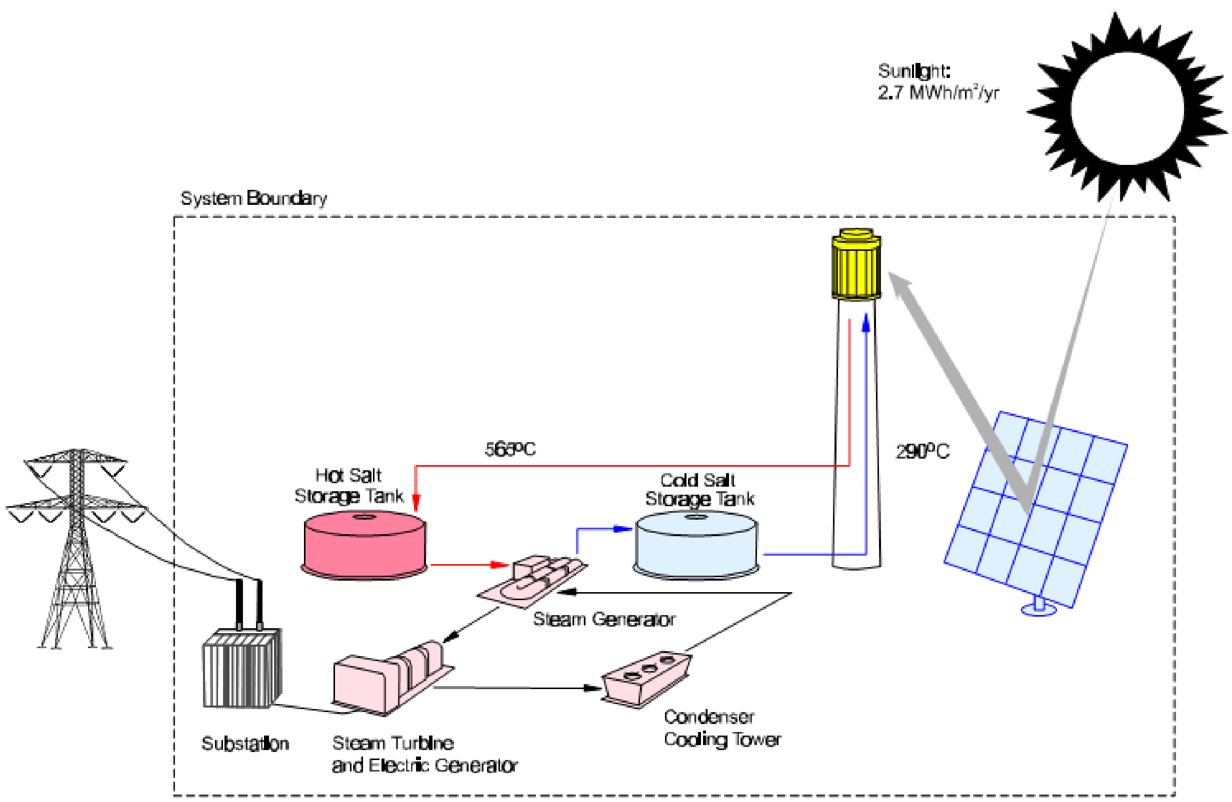


Figure 23. A schematic of atypical solar power tower system. The mirror reflects solar power onto a collector within the power tower. The power tower then sends the molten fluid through the Rankine cycle which generates electricity [37].

Parabolic Trough

Parabolic trough technology is proven to be one of the most low-cost technologies available in today’s world [38].This is largely due to the nine large commercial-scale solar power plants that have been operated in the California Mojave Desert since 1984. Typical parabolic dish engine systems can produce 15 to 300 MW of power [38]. The parabolic trough system consists of lines of concentrators that reflect and focus sunlight onto an absorber tube located along the focal line of the trough (see Figure 24 on page 83). A heat transfer fluid, generally water or oil, is pumped through this receiver tube to heat it. Typical operating temperatures range from 100-400˚C. A linear trough has typical concentrating factors between 10 and 100 and is located on a one-dimensional tracking system to maintain focus on the sun and the receiver tube. The heated fuel can be used in a thermal electric power plant, following a conventional Rankine cycle. Contemporary designs have achieved efficiencies of about 12% [37]. The main advantages to these systems are their modularity, allowing for linear of parallel placing, and their scalability, even though typical power plants tend to start at about 10MWe. The main drawbacks come from low heat levels and the need to operate large volumes of fuel, making water the most economical but not necessarily efficient fuel. This leads to losses in strong heat which have to be coupled with inefficiencies in the tracking system and the reflectivity and transmission of trough mirrors. Projected costs are still relatively high but lower than power towers – at about $3000/kW or less. However, because there is no heated fuel storage facilities, trough systems have to be coupled with natural gas or other combustibles in order to make the operating costs of an electricity-generating plant competitive. Furthermore a typical unit size range, even at its smallest is too large for our project, which was the principal reason for eliminating this option.

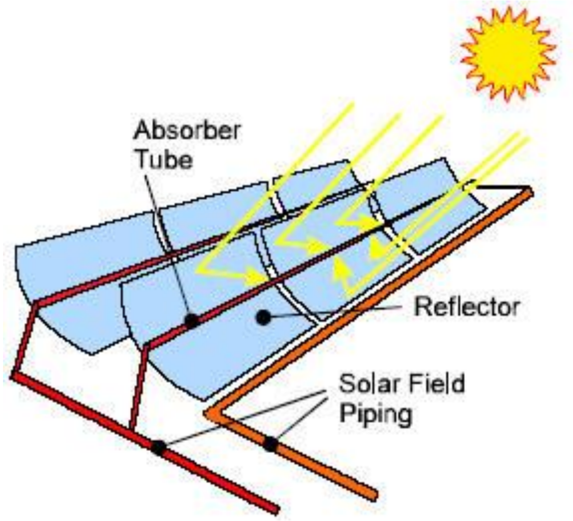


Figure 14. Typical design of a parabolic trough system. The sunlight hits the collectors which reflect the heat onto the absorber tubes through. The transfer fluid collects the heat and transfers it to a Rankine system of the same structure as in the solar power tower design [38].

Solar Dish Engine

Dish engines are composed of two parts: the concentrator, and the receiver and generator (see Figure 25 for a visual representation). Direct solar radiation strikes a dish and is concentrated by a factor of 600 – 3000 [38]. At the center of the dish lies a focal point that transfers the sun's energy to a heat engine. This engine used is the Stirling cycle engine, which converts heat to mechanical work. At the center of the focal point lies a two dimensional tracking system used to point the dish towards the sun to maximize heat absorption. These types of systems exhibit the highest efficiency amongst all solar power options, with efficiencies as high as 30%. This efficiency is twice as much as the efficiency provided by power towers, parabolic troughs, and photovoltaics. The use of Stirling cycle engine is a good candidate as it removes the excess thermal energy by using air as a working fluid. The advantages of this system specifically are the dispatchable electricity at a kW scale. The modularity of dish engine systems allows them to be deployed individually for remote applications or grouped together for village power. The power output for a typical dish engine is 5 – 50 kW. This output is suitable to power both Apatut and Las Delicias as both of those power requirements are within the 5 – 50 kW range. The Sterling dish engine was probably the most attractive option for our system. As a result, we decided to follow up and contact suppliers. The two main suppliers of solar dish engine systems in the United States are WGAssociates located in Dallas, Texas and Stirling Energy Systems (SES), a solar equipment company specializing in the Dish-Engine CSP technologies. Both of these companies were contacted in order to determine price and feasibility of implementing such a system. Unfortunately both companies denied our requests. We did not get a response from WGA. SES informed us that their CSP SunCatcher is in the development stage, and they are currently focused on deployment in the United States, with International deployment to follow at some point in the future (personal communication, SES, January 2011). Due to these responses we were unable to follow through with our design of using a solar dish engine.

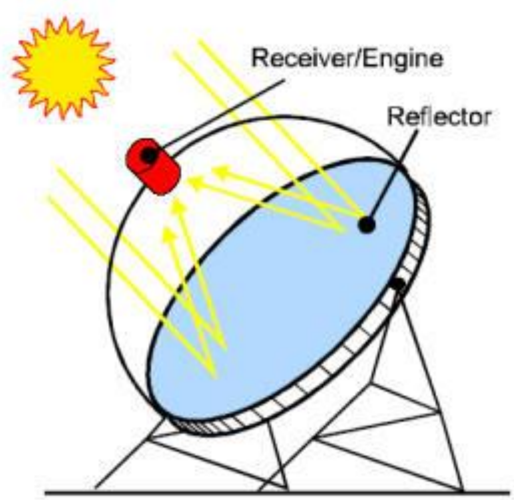


Figure 25. A standard design of a solar dish engine system. The sunlight rays collect on the reflector which focuses the collected heat on the receiver. The receiver then transfers the heat onto the engine. The engine is typically a Stirling heat engine that converts the heat power into mechanical work [37].

Wind Power

Wind power was considered as an alternative source of power supply for both projects. The Philippines in particular was looked at as having great potential for wind power due to its strong seasonal winds, especially on the northern island of Luzon on which Apatut is located. However, after a careful analysis of wind data presented by the National Renewable Energy Laboratory (2001), which collected wind data across the Philippines for twenty years, it was decided that Apatut was not located in a region where wind would be effective in harnessing power for the pump. NREL (2001) states that average wind speeds of at least 4 m/s are needed to produce a minimum of 100 W/m^2 [39].Unfortunately, Apatut lies in a valley where there is very poor high wind speed distribution, making it an unlikely candidate for even a minimum amount of power to be harnessed.

Wind power was also considered as an option in El Salvador. As with the Philippines, careful consideration of NREL (2005) data has demonstrated that the region where Las Delicias is located is a poor candidate for wind power [40].

Pump and Motor Selection

In looking for appropriate pumps for our systems, we focused on two types of pumps: positive displacement pumps and centrifugal pumps. Each type of pump has individual characteristics and it is important to distinguish between the two to determine which best fits the system in question. Additionally, we invested in AC pump motors instead of DC motors. The distinction between the two and the reasons for our final selection will also become apparent in this section.

Positive Displacement Pumps

Positive displacement (PD) machines impart energy via liquid or gas in a fixed displacement volume; that is, they create constant, fixed flow by enclosing a volume of liquid or gas at suction, moving it, and then releasing it [41]. The big advantage with PD pumps over centrifugal pumps is their ability to maintain constant flow regardless of head (see Figure 26). Furthermore, they are able to obtain very high heads; in fact it is common for PD pumps to operate at heads as high as 600 feet [42]. However, because they push flow in a piston – like motion, the flow comes out in a pulsed motion, an undesired feature for water supply systems. It is possible to alleviate the pulsed motion effect by increasing the number of pistons inside the pump, but this tends to greatly increase the price and size of the pump. PD pumps are typically used in heavy industrial applications because they can withstand high viscosity fluids and maintain great flow rate and efficiency. The downside to PD pumps is that they can only work in booster applications, and are not available in submersible models. Finally, because PD pumps are primarily used for industrial applications, their size and cost are enormous, far greater than is needed for either of the EWB project sites.

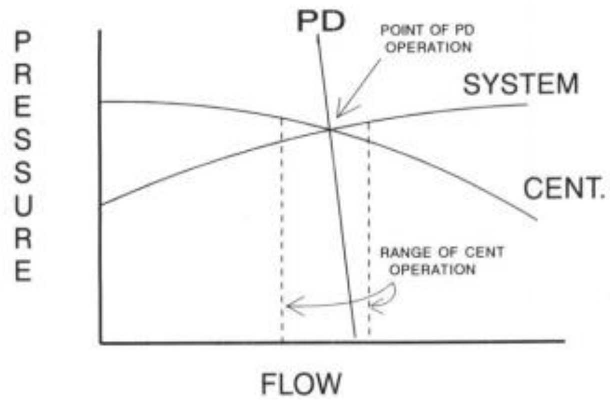


Figure 26. Comparison of performance curves for centrifugal and PD pumps. As demonstrated by the plot, PD pumps have limited flow rate variability associate with changing pressure; meanwhile, centrifugal pumps are strongly affected by a change in system pressure [43].

Centrifugal Pumps

Centrifugal pumps are the most widely type of pump used in industrial, domestic, and agricultural applications. Their advantage over PD pumps is their ability to provide a variety of flow rates, most of which are larger than those available with PD pumps. Unfortunately, their flow rates also strongly depend on head (pressure) of the system, and generally the flow rate decreases as head increases. Figure 25 demonstrates this effect and displays pump performance curves for both centrifugal and PD pumps. Centrifugal pumps are mostly used for low head applications, but if put in parallel may achieve fairly high head. Furthermore, their ability to be used for deep well purposes makes them the ideal candidate for the two project sites which require a submersible pump to move water from the well to the tanks. Their lower cost (as compared with PD pumps) and wider availability also qualify them as the optimal pump type for our systems' needs.

DC powered motors

The majority of solar powered water pumps are run by DC motors. This is because photovoltaic systems (which are predominantly used to power solar water pumps), produce DC voltage which is directly fed into the pump motor. DC motors are more efficient than AC motors and do not require a conversion system from DC to AC, gaining efficiency for the entire process. Unfortunately, DC motors are susceptible to more wear and tear than AC motors. Furthermore, although DC pumps operate at higher efficiencies, they are not suited to achieve high flow rate and high head, both of which are required for our two project sites [44, 45].

AC powered motors

AC motors cannot be directly supplied with power from solar panels. They require an inverter that converts DC to AC voltage which can be used to power the pump motor. This incurs some efficiency losses in the system. However, AC motor design is less reliant on brushes and other mechanical parts that can easily be damaged, and hence their lifetime is greater than that of DC motors [45, 46]. AC motors are also more economical because they have fewer parts within the design, and therefore require fewer maintenance and parts replacement over the lifetime of the motor [46]. Additionally, pumps powered by AC motors are able to provide high flow rates and operate at sufficiently high heads that are required by the systems in Apatut and Las Delicias.

Energy Storage

Heat Storage

Discussed within the *Alternative Analysis* section, parabolic troughs and power towers were also considered as possibilities for energy supply of water pumps. Both methods utilize a working fluid as a heat sink for solar energy. This working fluid is optimized with respect to heat transfer performance. With heat stored in the form of molten salts, it is possible to utilize the stored solar energy at times without direct sunlight, such as cloudy days or during the night. Currently working fluids are synthetic oils that have the necessary freezing (12°C) and boiling points (393°C) but are incapable of storing heat efficiently; rather, the heat is transferred to a second more efficient fluid, incurring additional efficiency losses along the way. The employment of a molten salt with similar freezing and boiling points improves the Rankine cycle efficiency, effectively reducing the area required for parabolic troughs. A drawback, however, is the relatively high freezing points of these salts ranging from about 130°C to 230°C, necessitating the need for increased caution to ensure the salts do not freeze within the system. A variety of salt mixtures were considered for use as heat transfer and storage fluids in parabolic troughs and power towers [47]; these are summarized in Table A30 which can be found in the Appendix, *Tables and Figures* . These considerations were not pursued further as it was decided thermal solar power systems will not be implemented, and that traditional photovoltaic panels would be employed as the primary source of energy.

Electrical storage

The use of photovoltaic panels as the primary energy source necessitated the consideration of electrical storage for pump use during the night time or on cloudy days when solar power was not readily available. Inclusion of a battery would also significantly reduce energy waste during inevitable spans of increased solar intensity when more power than the system needs is provided. The electrical energy requirements for the power systems implemented were stringent and specific: a battery must store large amounts of energy, in the order of tens of kilowatt hours, must able to discharge daily, and must be resilient under non-ideal storage conditions was necessary for the application of solar energy use. Although most battery types were considered, it was determined that the most suitable are deep cycle lead acid batteries [7]. These batteries are designed for longer life and are able to cycle as deep as 80 percent of rated capacity [8]. The configuration of the batteries matter as well. Through research conducted by Cassaca et al. (1996), it was concluded that the dual battery configuration minimized energy waste and improved efficiency by treating the batteries as separate entities. This configuration was able to charge the battery that was not being used while simultaneously utilizing the battery under load.

FUTURE CONSIDERATIONS

Rainwater Harvesting

Introduction

The purpose of instituting a rainwater catchment system is to increase the amount of water an individual may obtain without relying on the power grid. One of the major advantages to rainwater harvesting is that it can reduce storm drainage and flooding in streets. It also increases water conservation awareness, as individuals will want to keep their tank from drying up. Finally such systems are flexible, easy to maintain and do not require a labor-intensive approach. Interest in such a system is growing in many different areas of the developing world particularly where rainwater is abundant or where other means of water supply have been difficult. Current developing countries with well-established rainwater systems include North China, East Africa, and Singapore [48]. The water collected from such methods can either be treated to be used for potable purposes or to even be used for domestic purposes such as cleaning, irrigation, or toilet and laundry facilities.

The two villages discussed in this paper: Apatut and Las Delicias exhibit favorable circumstances towards rainwater harvesting. Both these villages have well distributed rainfall during wet and dry seasons especially in the case that obtaining water from the centralized piped supplies is unaffordable. The initial scope of our project was to be able to integrate domestic rainwater harvesting with other water supply options. The purpose of the following is usually used to provide partial to full coverage of water in the wet season and some coverage during the dry season. Furthermore, it is a short-term security against failure of the photovoltaic system to power the pumps and hence subject the villagers to no water. The following section describes the rainwater system, the different methods of rainwater harvesting considered, and finally the cost and feasibility of such a system.

While the benefits are great for our project, we have had to forego the implementation of a rainwater harvesting system due to its high costs and our desire to minimize capital investment. However, it must be considered in future recommendations for a possible implementation could easily take place if the EWB team is able to acquire the appropriate funds.

The basic system

The basic rainwater harvesting system is comprised of three main parts: collection surface, transporting mechanism, and water storage. The rain incident on a roof must be transported through a gutter or a pipe to a storage tank or cistern. Figure 27 shows typical rainwater schematic.

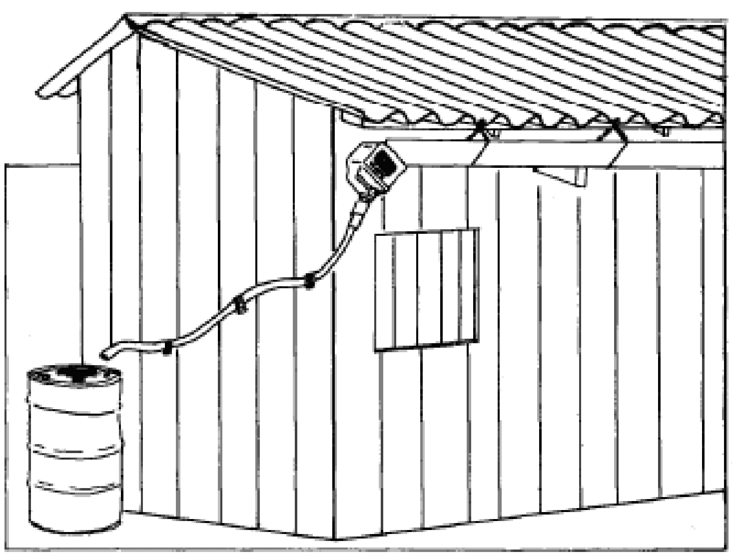


Figure 27: Typical Rainwater Harvesting Schematic (Design Recommendations).

Community Rainwater Harvesting:

A communal rain harvesting would involve a large catchment area because roofs are no longer available. Communal rain harvesting is a less complex manner however it involves various techniques of increasing run-off. Decreases in the permeability of the land surface are necessary to increase runoff. Current measures to deal with this include rainwater pump stations, dams, and elevated dikes. These measures deal with runoff in a chain of structures (management by line). The system is however susceptible to high rates of water loss due to infiltration into the ground and, because of the larger amount of water collected, storage is often more difficult and more susceptible to contamination. Figure 28 shows a typical ground catchment system. It may be better to create a number of detention ponds or storages on a small scale over the entire area on which the rain falls. This would not only prevent flooding, but also reduce the effect of drought. However these changes require the altering or clearing of land. [49].

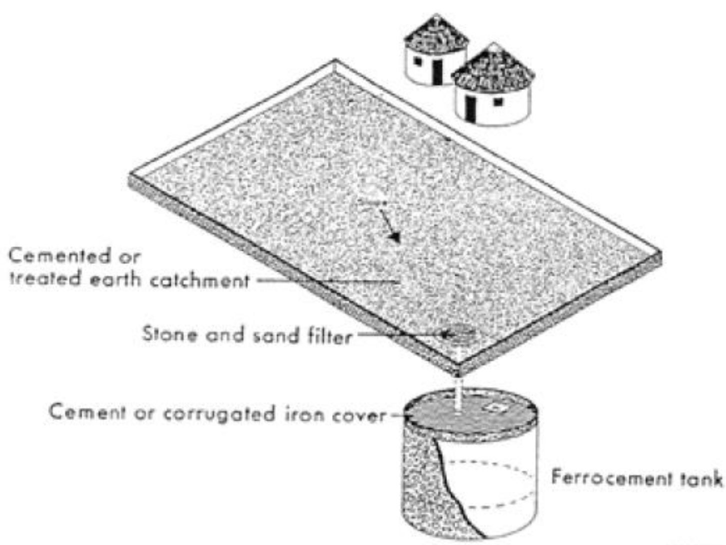


Figure 28: A typical ground catchment system [49].

Rooftop Rain Harvesting

Rooftop water harvesting supplies each individual with his or her own access to water, and eliminates the need to walk to a communal area to receive the water. This is important as it avoids having women and young children walk for what may amount to long hours to seek water [50]. Rooftop water harvesting eliminates the conflicts that arise from having to share water with neighbors and avoids the social issues associated with such.

The roof:

The roof is the first step in collecting the rainfall. An appropriate system cannot be employed with any type of roofing. A suitable surface must be hard, gable-like (sloped) and one that does not absorb water or pollute the run-off. Examples of suitable material include: tiles, metal sheet, plastics, and concrete. Unsuitable material include grass and palm-leaf roofs. In both Las Delicias and Apatut, the roofs in place are appropriate. Figure 29 shows two examples of houses in Apatut. The house to the left belongs to a lower class family and the one to the right belongs to an upper class family in the village. One house is made out of tin and the other terra cotta. Both of these materials are fit to catch run-off, and both roofs are gable.

Figure 29: The photograph on the left shoes a lower end home, whereas the one on the right shows an upper end home. Both houses are suitable for rainwater harvesting. (Amanda EWB, March 2011)

The rainfall falling off roofs is referred to as run-off. The run-off can be channeled into a tank or cistern to minimize the amount of water lost. Water collected from the roof is a function of area. The rainwater reaching the roof can be calculated from the roof area multiplied by the average monthly rainfall. However not all of the rain incident on the roof can be transferred to gutters and pipes and only 85% of the rain incident can actually be collected. The remaining 15% is lost due to evaporation and splashing. Equation 10 demonstrates how we were able to calculate the average amount of rainwater collected from each home.

$$\text{Rainfall} = (\text{Roof area})*(\text{monthly average rainfall})*(85\%) \qquad (10)$$

In dry seasons when most of the rain is drizzle, more than 15% of the rainwater will be lost to evaporation [51]. Table 30 summarizes the percentage of rainwater lost pertaining to each type of roof.

Table 30:Summary of types of roofs, run-off captured from each type, and contamination.

Type of Roof	Run-off Captured	Contamination
Galvanized Iron Sheets	>0.9	Excellent water quality; attracts high temperatures to help sterilize bacteria
Glazed Tile	0.6-0.9	Contamination may exist in tile joints; unglazed tile may harbor mold
Asbestos Sheets	0.8-0.9	Give good quality water if new; no evidence of carcinogenic effects by ingestion, older roofs harbor mold and moss

Las, Delicias, El Salvador

The estimated average water consumed by each individual in Las Delicias is 25 gallons per day. There are 470 households in the village with an estimated 6 individuals per house. Based on these estimates, each house must be supplied with at least 150 gallon of water per day all year to sustain the current population of Las Delicias without another source of water. Each roof in the village is assumed to be 15x15 feet, yielding an area of 225 ft^2. The maximum rainfall (reported in Table 31) occurs in August with .48 in/day [29]. Data collected is an average for each month over 22 years. Using Equation 10, the maximum rainfall collected from each house amounts to 57 gallons/day. This number is roughly sufficient for two individuals out of the six. The remaining 100 gallons/day must then be supplied through other means. The only way to increase the amount of collected water is through increasing roof area.

Table 31: Summary of monthly precipitation in Las Delicias, El Salvador (monthly averaged precipitation taken from NASA [29])

Month	Monthly Averaged Precipitation (in/day)	in/month	Gal/Day (total)	Gal/day/house
Jan	0.05	1.62	2978	6.33
Feb	0.05	1.63	3000	6.38
Mar	0.05	1.58	2911	6.19
Apr	0.07	2.08	3838	8.16
May	0.28	8.29	15243	32.41
Jun	0.38	11.55	21244	45.22
Jul	0.47	14.16	26031	55.41
Aug	0.49	14.64	26913	57.24
Sep	0.40	12.12	22281	47.45
Oct	0.30	9.17	16854	35.91
Nov	0.17	5.08	9331	19.82
Dec	0.11	3.41	6265	13.31

Apatut

The average water consumed by each individual in Apatut is slightly larger than that consumed in Las Delicias. This amounts to 30 gallons/day/person. The average roof size in Apatut is also larger, estimated to be 300 ft^2. Similar assumptions about average consumption are made with regards to the individuals in each household. The average monthly rainfall in Apatut is smaller, with maximum rainfall occurring during the month of September at 9.86 mm/day or .38 in/day [29]. Although the amount of rainfall in the Philippines is less than that in El

Salvador, given the larger roof size in the Philippines it is possible to collect more water per household, about 61.7 gallons/day/house. Once again this amount of water is only adequate for two individuals. The summary of average rainfall for each month in Apatut is listed in Table 32.

Table 32: Summary of monthly precipitation in Apatut, the Philippines [29].

Month	Monthly Averaged Precipitation (in/day)	in/month	Gal/Day (total)	Gal/day/house
Jan	0.03	1.02	797	5.32
Feb	0.03	0.83	647	4.32
Mar	0.03	0.78	610	4.07
Apr	0.06	1.72	1342	8.95
May	0.23	7.03	5501	36.71
Jun	0.33	9.78	7650	51.02
Jul	0.26	7.82	6120	40.81
Aug	0.29	8.94	6993	46.63
Sep	0.39	11.83	9256	61.74
Oct	0.24	7.28	5698	37.92
Nov	0.10	2.91	2281	15.21
Dec	0.05	1.45	1135	7.57

Gutters:

The second element involved in rainwater harvesting is guttering. It is the cheapest of the three elements and most often neglected in many systems. To facilitate the transport of water from the roof to the storage tank, it is essential to install roof gutters. Guttering can protect a building from damp penetration, erosion, and water damage to the foundation of the house. In developing countries, gutters are often a luxury and as a result have been replaced by roof overhang to provide shade and send running water down the walls. Failure to install guttering, leads to high loss of run-offs and to some extents failure of the rain system altogether.

Layout:

Possible guttering layouts can vary depending on the orientation of the roof. The layout of gutters can either maximize rainfall captured or minimize rainfall captured. During the research process we came across different forms of constructing the gutters on the roof. Due to the nature of the roofs in Las Delicias and Apatut, the gutter layout can be simplified to three different schematics. In the case of Las Delicias, gutters exist on both edges of the roof; however that is not the case with Apatut as there are no gutters on the roof. As a result, different gutter orientations were studied and the optimal layout was chosen based on feasibility and cost.

The first system is referred to as the "simple informal" system. It consists of placing gutters on only one side of the roof [51]. Although this is the simplest and cheapest system it only collects water from half of the roof's area. Figure 33 shows the schematic of such a system.

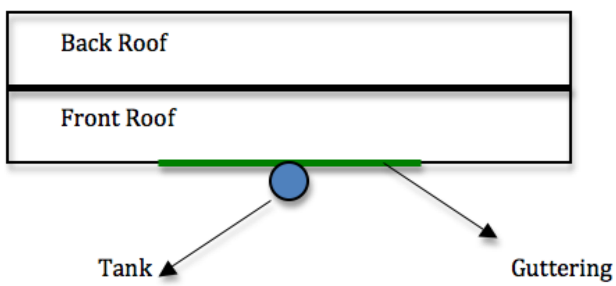


Figure 33: Schematic of "simple informal" system.

The second system studied is referred to as the front and back system. Unlike the "simple informal" system which collects water from just one side of the roof, the front and back system captures water from both the front and back sides of the roof, hence its name. The drawback to this system is that it requires an additional tank at the back side of the roof. Since tanks are the most expensive component of a rainwater system, this method was eliminated for both Apatut and Las Delicias as it was not economically feasible. Figure 34 on page 100 shows the schematic of such a system.

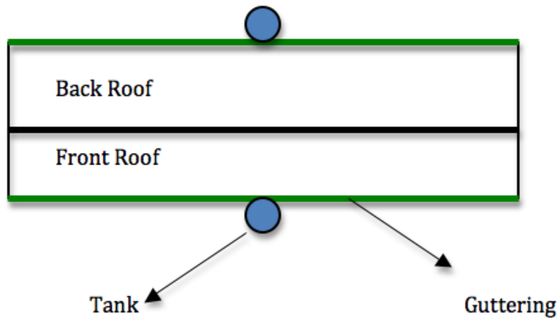


Figure 34: Schematic of front and back system.

The last system studied combines the first two systems. Gutters are positioned in a sloped fashion and downspouts are used to guide the descent of the water into the tank [51]. This is system was deemed optimal because it economizes on tank costs and encompasses total roof area. As a result, the rainfall collected is maximized while costs are minimized. Figure 35 demonstrates the schematic of this type of system.

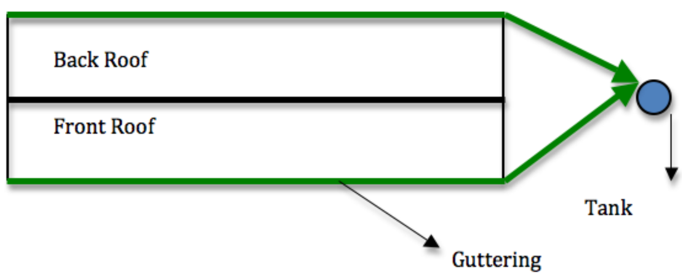


Figure 35: Schematic of sloped system.

Shape and size:

The size and shape of a gutter affect both its ability to catch and transport run-off. As a result the ideal gutter should be very wide to avoid overflow and enclose a larger area for transport of more water volume. The final constraint on the design is gutter perimeter. To reduce costs, the gutter must be of the smallest perimeter possible. Three different cross sections were analyzed during the research: circular, rectangular, and trapezoidal.

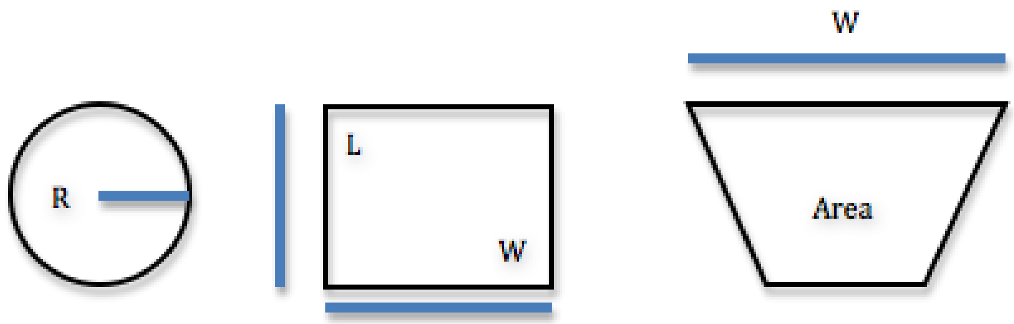


Figure 36: Cross-sectional area of different gutters: circular, rectangular, and trapezoidal

The trapezoidal shape is superior because it has a smaller perimeter and larger area. This entails that less material is needed. Neither leaves nor twigs block these trapezoid shaped gutters, as would a V-shape, which could potentially work since it has a high area to perimeter ratio as the trapezoid.

Finally the size of the gutter is crucial to consider when seeking to avoid overflow and loss of run-off. During wet seasons, when rainwater is falling at a greater capacity, overflow of gutters can be expected. In the dryer seasons a small gutter will suffice in carrying all the rainwater. In tropical regions such as Apatut and Las Delicias, 10% of rainwater falls at a rate of 0.08 in/min or more. This helps us correctly size the gutters based on rate of water being received [51]. Rainfall at much higher intensities will result in lost run-off due to the excess water; however this loss is assumed negligible (2-3%) in comparison to the amount of water obtained. Table 37 summarizes the recommended gutter size based on varying roof areas with an assumed rainfall rate of 0.08 in/min.

Table 37: Recommendations of gutter widths and downspout diameters based on roof area.

Roof Area (ft^2)	Recommended Gutter width (in)	Recommended Downspout diameter (in)
110	2.00	0.60
225	2.50	1.00
310	3.00	1.25

The data from Table 37 allows us to conclude that gutters of 2.50 inches width and downspout diameter of 1.00 inches are best suited for Las Delicias. The recommended sizing for Apatut would be slightly larger at 3 inch gutters and 1.25 inch diameter downspouts. The main suppliers for these types of gutters can be sourced from the Philippines, El Salvador, or the United States. From the Philippines, Atlanta Duracon PVC Gutter is a wholesale distributer and supplier of gutters, downspouts, and pipes. The gutters for El Salvador can be best supplied from the United States from GutterSupply Company, a division of Rain Trade Corporation. Costs will be analyzed later in the paper.

Tanks:

The final and most important step in any rainwater harvesting system is the storage component. This element possesses the greatest cost burden. Many rain-harvesting projects have failed because poor households could not afford to buy large enough tanks to capture run-off from their roofs. Therefore the main incentive in this project is to seek adequate and cost-effective tanks. The tanks chosen for rainwater harvesting are ferrocement tanks. For discussion of tanks see page 63.

Requirements:

Similar requirements hold for rainwater harvesting tanks. For discussion of tank requirements see page 63. Further requirements advise against the use of dipping buckets to collect water from the tank. Although the problem statement itself did not stress on filtration, the tanks used for rainwater harvesting must be able to exclude mosquitoes as much as possible as well as be placed away from sunlight, as exposure to sunlight could lead to the growth of algae. Finally and most importantly the tanks must be accessible for cleaning [51].

Alternatives:

An alternative to building an overground tank is an underground tank. This would probably be the cheapest option because we could save up on a lot of material by using soil. However the soil used must be suitable and able to take the weight of the water. There will be a waterproof layer to avoid the water from seeping into the soil. Such a structure could be advantageous as it would have a hemispherical shape. However, issues may arise with price of digging and the perhaps the greatest issue is increased contamination by leaks or rising water. Due to this we out ruled underground tanks as a feasible option.

Costs:

Although rainwater harvesting serves as a great alternative to our system during times of pump shutdown or when the PV cells may not be working, the cost analysis led us to conclude it unfeasible at the current time. Consequently, rainwater harvesting was not included in our final design. However because of the potential that it could create a self-sustainable village, it is highly recommended that this design be implemented once the project has taken place and further investments can be collected. The following costs are summarized below in Table 38 and 39 for Apatut and Las Delicias.

Table 38: Figures used to estimate costs

Data For	Las Delicias	Apatut
Roof Side (ft)	15	15
House Height (ft)	8	20
Roof Area (ft)	225	300
Total Gutters	46	70
Total Gutters Needed	16	70
Households	470	150
People/Household	6	6
Rainwater Efficiency	0.85	0.85

Table 39: Estimated Costs for Las Delicias, and Apatut

Average Tank~250 gallons	Las Delicias Cost	Apatut Cost
Gutters/ft	$1.50	$1.50
Wire mesh	$20	$20
Wire Netting	$15	$15
Cement	$8	$8
Sand	$2	$2
Water	$5	$5
Downspout x2	$18	$18
Elbow x2	$2	$2
Gutter Filter/ft	$2.00	$2.00
Tank Cost	$50	$50
Total Cost/house	$186.00	$315.00
Total Cost	$87,420.00	$47,250.00

Las Delicias, El Salvador

From Table 33 the total investment for rainwater harvesting for Las Delicias is shown to be around $87,000. The cost for implementing the project is only $186 for each house. The individual tank minimizes on costs as it only amounts to $50. This price is also an overestimation. If we take the maximum rainfall in Las Delicias to be 57 gallons/day/house, then a 250-gallon tank could hold roughly what is equivalent to 4-5 days of water. In the dryer seasons, the tank is expected to be not as full. A tank of 1m^3 is roughly equivalent to 264 gallons requires 1 bag of 50 kg cement, and 1 kg of steel wire or wire mesh [16]. The average price for a 50 kg bag of cement ranges between $1-$10. This means that the tank could potentially cost lower than $45 per household.

Apatut, the Philippines

From Table 33, the total investment for rainwater harvesting in Apatut is roughly $47,000. Unlike Las Delicias, the investment in Apatut is less expensive. The reason for the large discrepancy in costs is due to the smaller number of households in Apatut, which amounts to approximately 150. However, the total cost for implementing a rainwater system is almost twice as large. The total cost for each house is $315. This is more expensive than Las Delicias because there are no gutters in Apatut. As a result costs increase in gutters and in gutter filters. If we take the maximum rainfall in Apatut to be 62 gallons/day/household, a 250-gallon tank could hold what is equivalent to 3-4 days of water. The reason the tank volume was estimated to hold 250 gallons follows the same reasoning we used for Las Delicias. When consulting several sources, it was found more economical to build a larger tank (i.e. using a 50 kg bag of cement, because most suppliers in both the Philippines and El Salvador sell cement as 50 kg/bag). Table 40 summarizes the specific materials and suppliers for Philippines and El Salvador. A 1:3 ratio is the basis for determining the cement: sand ratio, and a 2:1 ratio in determining the water: cement [16].

Table 40: Cement, sand and water needed for a typical 250-gallon tank.

Location	Cement [52, 53]	Sand	Water	Supplier
Philippines	50 kg (110 lbs)	150 kg (330 lbs)	25 L (6.6 gal)	SealLinkage INTL INC
El Salvador	50 kg (110 lbs)	150 kg (330 lbs)	25 L (6.6 gal)	Electrama

Recommendations

Rainwater harvesting systems can be a useful addition to any system. They are easy to manage, operate, and mostly depend on existing structures. Such a system has very few negative environmental impacts as compared to other technologies. The water collected from rain is relatively clean and the quality is often better than that of underground water. It usually requires little or even no treatment, especially when used for non-potable reasons. Most importantly this type of system can co-exist with other water sources, as it provides a good supplement to obtaining clean water. It is often the cheapest way to get water when not relying on electrical pumps. One of the main advantages is that it provides a buffer or security in times of equipment breakdown such as pumps, PV cells, or even natural disasters that leave many individuals of poorer countries with no source of water. Finally because the system is easy to build, and requires little or no intensive and skilled labor it can often be operated anywhere and everywhere.

The scope of our project and emphasized on minimizing the budget, this did not allow us to include rainwater harvesting in our final design. Our total capital investment, although small compared to other projects is completely based on philanthropic funds. Still we were able to create a rainwater harvesting system that can sustain two villages with very little costs. In Las Delicias for instance, the EWB estimated that such as project would could $170,000; we managed to lower these costs by roughly 50%, as our design only costs $87,000. In Apatut there was no consideration for rainwater harvesting, and such a design could potentially be implemented in the future once the systems we proposed are running.

In the larger scope, we created a self-sufficient water supply system without being dependent on remote sources. In doing so we decreased reliance from a pipeline drawing water from a spring. When a city or village is reliant on a centralized water supply, it is vulnerable in the face of a natural disaster or technical problems that could cause power shutdown. In Las

Delicias for instance, the villagers can only receive water twice a week because they cannot afford to pay the electrical bill. This high reliance on a centralized system is unsustainable. Therefore rather than having a centralized water system, we wanted to create a point system. This basically emphasizes the decentralization of water sources by creating numerous scattered water points. In Apatut, there is currently no water system but the villagers have to walk several miles from their homes to receive water from wells or creeks. This practice is both unsustainable and highly risky. This is largely a result of the shallow creeks and wells that cause impurities to rise quickly to the surface and contaminate the only source of drinking water the villagers have. Therefore the design discussed could avoid such problems if and when implemented in the near future.

CONCLUSION AND RECOMMENDATIONS

The scope of this project was to provide low-cost, sustainable source of power for the water pumps in both Las Delicias and Apatut. After considering several options for power, we selected the photovoltaic cell system for both project sites. The PV system maintenance costs were determined to be more affordable than the current electricity source, and achieved its goal of providing low-cost power to the villages.

The initial investment in the power system in Las Delicias was determined to be $120,000, and includes a new tank, PV modules and related components, batteries, and three pumps and their related parts (motor, control box). Although the initial investment in this system is high, we determined that using PV modules provides the village with low-cost monthly maintenance, significantly reducing monthly electricity bills. Whereas the residents now pay as much as $24,000 for their annual electricity needs (with regards to the water pump), having the PV system will reduce their costs to approximately $200 per year. Moreover, the IRR for this project was determined to be very profitable and calculated to be 36%. Our new design for the Las Delicias location also addresses the issues of water distribution, ensuring that the entire community gets the water they for which they paid. Although this was outside the scope of our project, we thought it an important part to address; we want all the residents of Las Delicias to benefit from the water distribution system into which so much investment is going.

The water system in Apatut is much smaller than the system in Las Delicias, and hence our costs are also reduced. The investment in the power system in Apatut was determined to be $22,000 and includes the PV modules and related parts and the submersible pump. Since no hydraulic system changes were made and the original EWB-MAP design was used, the tank was left out of the investment as it is assumed that it will be provided by the EWB-MAP team. The electricity costs from the grid in Apatut are undetermined because Apatut currently does not use the grid to power anything. However, we determined that the annual maintenance costs for the PV system was less than $20, which will certainly be lower than the electricity bills from the grid.

Given the charitable nature of this project, it was very difficult to determine a method of analyzing the financial benefits such a project will bring to a prospective investor. Water has a very strong correlation with economic development of a community. A lack of access to clean drinking water increases the potential of water related diseases in both adults and children. Trachoma, diarrhea, and other water borne diseases account for more than 1.5 million children dying each year [54]. They also contribute to over 400 million school day and over 300 million work days lost [55 and 56]. It is not hard to see the impact that water will have on a developing community. Unfortunately, quantizing this effect is what has prevented many investors in allocating much needed funds toward water related projects such as the ones designed for Las Delicias and Apatut. A typical investor requires a return on his investment into his own bank account. The problem with water development projects is that they benefit the individuals receiving the water and the society into which these individuals are adding their productivity. The investor as an individual hardly gets any financial return (except maybe if he charges the villagers monthly until the debt is repaid; this, however, defeats the purpose of the project, whose aim is to aid in the economic and social development of said community). Thus, all of the NPV and IRR numbers calculated seem irrelevant, since no one is actually getting any hard cash for the money they have invested.

This dilemma motivated us to look at these development projects from the stand point of the government, an investor of its kind. Because the return on these types of investments will be felt across society, and not just by one person, government is the ideal investor. Through an increase of well-being and productivity of its citizens, it makes a great return on any money it spends on the residents through taxes it collects and through a large deferment of any medically related expenses. Regrettably, many governments do not look at water related projects as investment into the entire economy. This stems from the unfortunate misunderstanding of the "universal right to water," which makes a lot of residents (this is seen quite a bit outside the US) believe that water should be free and fully subsidized by the government. This public water market creates the illusion of investment losses, whereas in reality, all the secondary benefits reaped from access to clean water go unnoticed.

Although our project largely dealt with supplying affordable power for water pumps, and not intended to revolutionize the thinking behind water related projects and the need for their investment, we hope that we provided the reader with some insight into the benefits that often go unnoticed because of a lack of a big dollar attached to them. These projects affect real people and have real, positive consequences on everyone involved.

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APPENDIX

Tables and Figures

Table A1. The data for Las Delicias, El Salvador system. Section 2 is the pipe carrying water from the well to the new tank. Submersible pump.

Q	u	Re	f_F	head loss (pipe)		head loss (fittings)	static height	TDH height	Pump	
				Drop pipe	section 2					
[gpm]	[m/s]	-	-	[ft]	[ft]	[ft]	[ft]	[ft]	[hp]	[kW]
10	0.03457	5258	0.009255	0.0030	0.172	0.000222	476	477	2.21	1.66
20	0.06913	10515	0.007738	0.010	0.575	0.000743	476	477	4.42	3.31
30	0.1037	15773	0.007022	0.021	1.174	0.001517	476	478	6.63	4.98
40	0.1383	21030	0.006577	0.036	1.955	0.002527	476	478	8.86	6.64
50	0.1728	26288	0.006264	0.054	2.910	0.00376	476	479	11.10	8.32
60	0.2074	31545	0.006028	0.075	4.032	0.005211	476	480	13.35	10.01
70	0.2420	36803	0.005842	0.099	5.318	0.006873	476	482	15.61	11.71
80	0.2765	42060	0.005689	0.126	6.765	0.008742	476	483	17.90	13.42
90	0.3111	47318	0.005561	0.156	8.370	0.01082	476	485	20.20	15.15
100	0.3457	52575	0.005452	0.189	10.13	0.01309	476	487	22.53	16.90
110	0.3802	57833	0.005358	0.224	12.04	0.01557	476	489	24.89	18.66
120	0.4148	63090	0.005275	0.263	14.11	0.01824	476	491	27.27	20.45
130	0.4494	68348	0.005201	0.304	16.33	0.02110	476	493	29.67	22.26
140	0.4839	73605	0.005135	0.348	18.70	0.02416	476	495	32.11	24.08
150	0.5185	78863	0.005075	0.395	21.22	0.02742	476	498	34.58	25.94
160	0.5531	84120	0.005021	0.445	23.88	0.03086	476	501	37.09	27.82
170	0.5876	89378	0.004972	0.498	26.70	0.03450	476	504	39.64	29.73
180	0.6222	94635	0.004927	0.553	29.66	0.03833	476	507	42.22	31.66
190	0.6568	99893	0.004885	0.611	32.77	0.04235	476	510	44.84	33.63
200	0.6913	105150	0.004847	0.672	36.02	0.04655	476	513	47.51	35.63
210	0.7259	110408	0.004811	0.735	39.42	0.05094	476	517	50.22	37.67
220	0.7605	115665	0.004778	0.801	42.97	0.05552	476	520	52.98	39.74
230	0.7950	120923	0.004747	0.870	46.66	0.06029	476	524	55.79	41.84
240	0.8296	126180	0.004718	0.941	50.49	0.06525	476	528	58.65	43.99
250	0.8642	131438	0.00469	1.016	54.47	0.07039	476	532	61.57	46.17
260	0.8987	136695	0.004665	1.093	58.59	0.07571	476	536	64.53	48.40
270	0.9333	141953	0.00464	1.173	62.85	0.08122	476	540	67.56	50.67
280	0.9679	147211	0.004617	1.255	67.26	0.08692	476	545	70.65	52.98
290	1.002	152468	0.004596	1.340	71.81	0.09280	476	550	73.79	55.34
300	1.037	157726	0.004575	1.427	76.51	0.09887	476	554	77.00	57.75

Table A2. The data for the Las Delicias, El Salvador system. Booster pump to tank 1

Q	u	Re	f_F	head loss	fittings loss	static height	TDH height	Pump	
[gpm]	[m/s]	-	-	[ft]	[ft]	[ft]	[ft]	[hp]	[kW]
2	0.03982	2524	0.01132	0.3779	0.0008420	300	300.8	0.28	0.21
4	0.07964	5047	0.009281	1.239	0.002760	300	301.7	0.56	0.42
6	0.1195	7571	0.008315	2.497	0.005564	300	302.9	0.84	0.63
8	0.1593	10094	0.007712	4.118	0.009174	300	304.5	1.13	0.85
10	0.1991	12618	0.007287	6.079	0.01354	300	306.5	1.42	1.06
20	0.3982	25236	0.006158	20.55	0.04579	300	321.0	2.97	2.23
30	0.5973	37854	0.005611	42.13	0.09387	300	342.6	4.76	3.57
40	0.7964	50472	0.005266	70.28	0.1566	300	370.9	6.87	5.15
50	0.9955	63090	0.005019	104.7	0.2332	300	405.3	9.38	7.04
60	1.195	75708	0.004829	145.0	0.3232	300	445.8	12.38	9.29
70	1.394	88326	0.004678	191.2	0.4260	300	492.1	15.95	11.96
80	1.593	100944	0.004552	243.1	0.5415	300	544.0	20.15	15.11
90	1.792	113562	0.004446	300.4	0.6694	300	601.5	25.06	18.80
100	1.991	126180	0.004354	363.2	0.8093	300	664.4	30.76	23.07
110	2.190	138798	0.004273	431.4	0.9611	300	732.7	37.32	27.99
120	2.389	151417	0.004202	504.8	1.125	300	806.3	44.79	33.60
130	2.588	164035	0.004138	583.4	1.300	300	885.1	53.27	39.95
140	2.787	176653	0.004080	667.1	1.486	300	969.0	62.81	47.10
150	2.987	189271	0.004027	755.9	1.684	300	1058.0	73.47	55.10
160	3.186	201889	0.003979	849.7	1.893	300	1152.0	85.34	64.00
170	3.385	214507	0.003934	948.5	2.113	300	1251.1	98.46	73.85
180	3.584	227125	0.003893	1052	2.345	300	1355.0	112.92	84.69
190	3.783	239743	0.003855	1161	2.587	300	1463.9	128.77	96.58
200	3.982	252361	0.003819	1274	2.839	300	1577.6	146.08	109.56
210	4.181	264979	0.003786	1393	3.103	300	1696.2	164.91	123.68
220	4.380	277597	0.003754	1516	3.377	300	1819.6	185.33	139.00
230	4.579	290215	0.003725	1644	3.662	300	1947.8	207.40	155.55
240	4.779	302833	0.003697	1776	3.958	300	2080.7	231.19	173.39
250	4.978	315451	0.003670	1914	4.264	300	2218.3	256.75	192.56
260	5.177	328069	0.003645	2056	4.580	300	2360.6	284.15	213.11
270	5.376	340687	0.003621	2202	4.907	300	2507.6	313.45	235.09
280	5.575	353305	0.003599	2354	5.244	300	2659.3	344.72	258.54
290	5.774	365923	0.003577	2510	5.591	300	2815.5	378.01	283.51
300	5.973	378541	0.003556	2670	5.949	300	2976.4	413.39	310.04

Table A3. The data for the Las Delicias, El Salvador system. Booster pump to tank 3. The pipeline to booster tank 3 changes in diameter halfway from the Cruzero to the tank. The diameter of the first section is 4 inches, while the diameter of the second section is 3 inches.

Q	u_1	u_2	Re_1	Re_2	f_{r1}	f_{r2}	head loss Section 1	head loss Section 2	fittings loss	static height	TDH height	Pump	
[gpm]	[m/s]	[m/s]	-	-	-	-	[ft]	[ft]	[ft]	[ft]	[ft]	[hp]	[kW]
10	0.077	0.138	7886	14020	0.008222	0.007095	0.338	0.456	0.0023	200	201	0.93	0.7
15	0.116	0.207	11829	21030	0.007403	0.006427	0.685	0.924	0.0047	200	202	1.4	1.05
20	0.155	0.276	15773	28040	0.006889	0.006006	1.134	1.530	0.0078	200	203	1.88	1.41
25	0.194	0.345	19716	35050	0.006525	0.005707	1.678	2.264	0.0116	200	204	2.36	1.77
30	0.233	0.414	23659	42060	0.006247	0.005478	2.314	3.121	0.0159	200	206	2.86	2.14
35	0.272	0.483	27602	49070	0.006025	0.005295	3.038	4.097	0.0209	200	207	3.36	2.52
40	0.311	0.553	31545	56080	0.005842	0.005143	3.847	5.189	0.0265	200	209	3.88	2.91
50	0.388	0.691	39431	70100	0.005554	0.004904	5.714	7.707	0.0394	200	214	4.95	3.71
60	0.466	0.829	47318	84120	0.005333	0.004721	7.901	10.66	0.0545	200	219	6.08	4.56
70	0.544	0.967	55204	98140	0.005156	0.004574	10.4	14.03	0.0717	200	225	7.28	5.46
80	0.622	1.106	63090	112160	0.00501	0.004452	13.20	17.80	0.0909	200	231	8.57	6.43
90	0.700	1.244	70976	126180	0.004886	0.004348	16.29	21.97	0.1122	200	239	9.94	7.46
100	0.777	1.383	78863	140200	0.004779	0.004259	19.67	26.53	0.1355	200	247	11.42	8.56
110	0.855	1.521	86749	154221	0.004685	0.004181	23.33	31.47	0.1608	200	255	13	9.75
120	0.933	1.659	94635	168241	0.004602	0.004111	27.27	36.78	0.1879	200	265	14.7	11.02
130	1.011	1.797	102522	182261	0.004527	0.004049	31.49	42.47	0.217	200	274	16.52	12.39
140	1.089	1.936	110408	196281	0.004459	0.003993	35.97	48.52	0.2479	200	285	18.47	13.85
150	1.167	2.074	118294	210301	0.004398	0.003941	40.72	54.93	0.2806	200	296	20.57	15.43
160	1.244	2.212	126180	224321	0.004341	0.003894	45.74	61.7	0.3152	200	308	22.82	17.11
170	1.322	2.351	134067	238341	0.004289	0.003851	51.02	68.81	0.3516	200	320	25.22	18.92
180	1.4	2.489	141953	252361	0.004241	0.003811	56.55	76.28	0.3897	200	334	27.79	20.84
190	1.478	2.627	149839	266381	0.004197	0.003773	62.35	84.1	0.4297	200	347	30.54	22.9
200	1.556	2.765	157726	280401	0.004155	0.003739	68.39	92.25	0.4713	200	361	33.46	25.1
210	1.633	2.904	165612	294421	0.004116	0.003706	74.69	100.8	0.5148	200	376	36.58	27.43
220	1.711	3.042	173498	308441	0.004079	0.003675	81.24	109.6	0.5599	200	392	39.89	29.92
230	1.789	3.18	181384	322461	0.004044	0.003646	88.04	118.8	0.6067	200	408	43.41	32.56
240	1.867	3.318	189271	336481	0.004011	0.003619	95.09	128.3	0.6553	200	424	47.14	35.36
250	1.944	3.457	197157	350501	0.00398	0.003593	102.4	138.1	0.7055	200	441	51.09	38.32
260	2.022	3.595	205043	364521	0.003951	0.003569	109.9	148.3	0.7574	200	459	55.27	41.46
270	2.1	3.733	212929	378541	0.003923	0.003546	117.7	158.7	0.811	200	478	59.69	44.77
280	2.178	3.872	220816	392561	0.003896	0.003523	125.7	169.6	0.8663	200	496	64.35	48.26
290	2.256	4.01	228702	406581	0.00387	0.003502	134	180.7	0.9232	200	516	69.26	51.94
300	2.333	4.148	236588	420601	0.003846	0.003482	142.5	192.1	0.9817	200	536	74.42	55.82

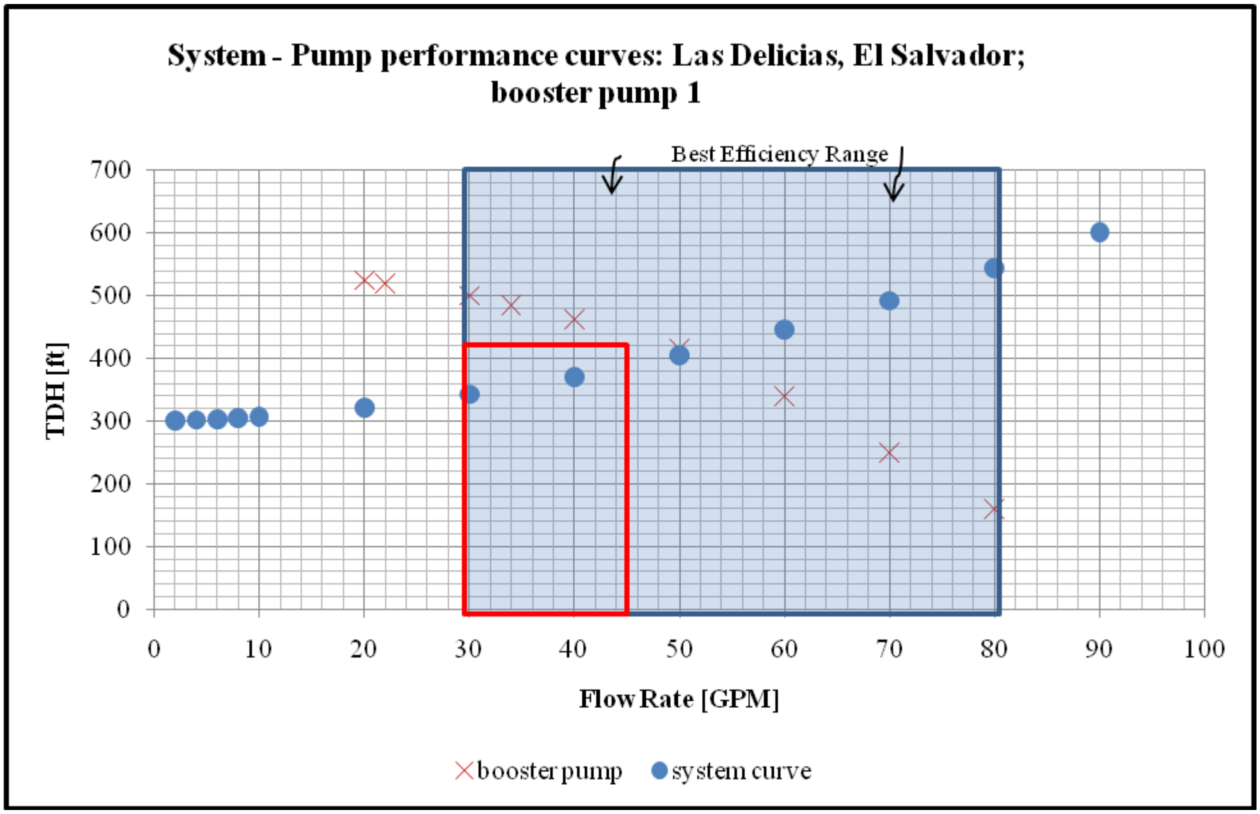


Figure A4. System – Pump performance curve for Las Delicias, El Salvador; booster pump to tank 1.

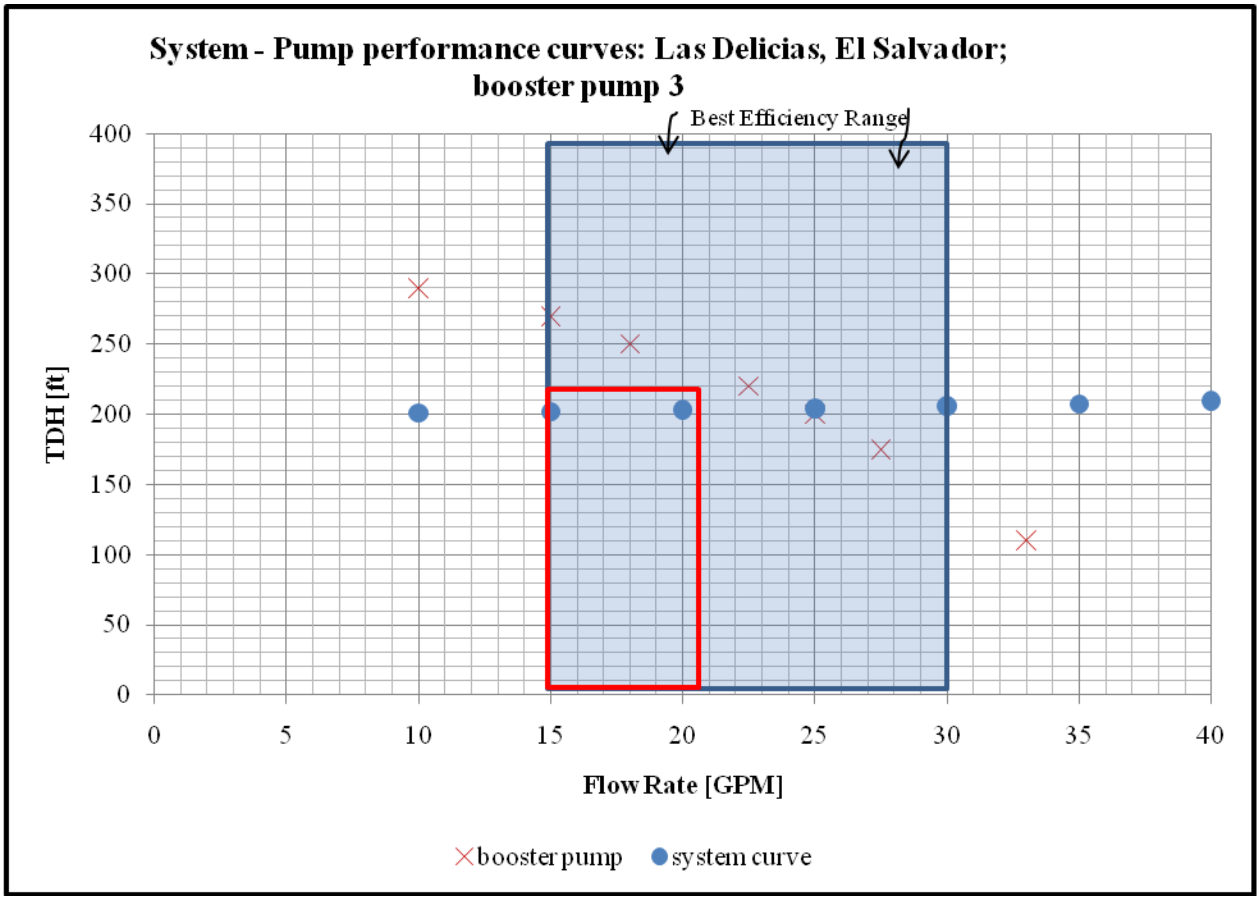


Figure A5. System – Pump performance curve for Las Delicias, El Salvador; booster pump for tank 3.

			Submerrsible Tank						TANK 1						TANK 3					
		25	**80000**	Sub Pump (gal)	sum of need	pump accum	difference	GPM	**23625**		sum of need	pump accum	difference	GPM	**11375**		sum of need	pump accum	difference	GPM
0	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
1	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
2	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
3	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
4	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
5	0%	0	**0**	0	0	0	0		**0**		0	0	0		**0**		0	0	0	
6	3%	0.75	**2400**	0	2400	0	-2400		**709**		709	0	-709		**341**		341	0	-341	
7	3%	0.75	**2400**	0	4800	0	-4800		**709**		1418	0	-1418		**341**		683	0	-683	
8	4%	1	**3200**	0	8000	0	-8000		**945**		2363	0	-2363		**455**		1138	0	-1138	
9	7%	1.75	**5600**	8889	13600	8889	-4711	148	**1654**	2625	4016	2625	-1391	44	**796**	1264	1934	1264	-670	21
10	7%	1.75	**5600**	8889	19200	17778	-1422	148	**1654**	2625	5670	5250	-420	44	**796**	1264	2730	2528	-202	21
11	7%	1.75	**5600**	8889	24800	26667	1867	148	**1654**	2625	7324	7875	551	44	**796**	1264	3526	3792	265	21
12	7%	1.75	**5600**	8889	30400	35556	5156	148	**1654**	2625	8978	10500	1523	44	**796**	1264	4323	5056	733	21
13	5%	1.25	**4000**	8889	34400	44444	10044	148	**1181**	2625	10159	13125	2966	44	**569**	1264	4891	6319	1428	21
14	5%	1.25	**4000**	8889	38400	53333	14933	148	**1181**	2625	11340	15750	4410	44	**569**	1264	5460	7583	2123	21
15	5%	1.25	**4000**	8889	42400	62222	19822	148	**1181**	2625	12521	18375	5854	44	**569**	1264	6029	8847	2818	21
16	5%	1.25	**4000**	8889	46400	71111	24711	148	**1181**	2625	13703	21000	7298	44	**569**	1264	6598	10111	3514	21
17	9%	2.25	**7200**	8889	53600	80000	26400	148	**2126**	2625	15829	23625	7796	44	**1024**	1264	7621	11375	3754	21
18	9%	2.25	**7200**	0	60800	80000	19200		**2126**		17955	23625	5670		**1024**		8645	11375	2730	
19	9%	2.25	**7200**	0	68000	80000	12000		**2126**		20081	23625	3544		**1024**		9669	11375	1706	
20	9%	2.25	**7200**	0	75200	80000	4800		**2126**		22208	23625	1418		**1024**		10693	11375	683	
21	3%	0.75	**2400**	0	77600	80000	2400		**709**		22916	23625	709		**341**		11034	11375	341	
22	3%	0.75	**2400**	0	80000	80000	0		**709**		23625	23625	0		**341**		11375	11375	0	
23	0%	0	**0**	0	80000	80000	0		**0**						**0**					

9	Pump Hours Used	Pump	**GPM**	**kW**	**kWH**	GPH	Day Before	Hours of Pumping	Min Tank Vol (Gal)
		New	148.15	21.60	194.20	8889	8000	0.90	26400
		1	43.75	2.92	26.30	2625	2363	0.27	
		3	21.06	0.94	8.44	1264	1138	0.13	
				25.46	228.94				

Table A6. Scenario 1 for the pump schedule in Las Delicias, El Salvador. This scenario outlines the maximum number of PV modules needed as only 9 hours of pumping is scheduled. Tank 1 and 3 requirements are based on the population of villagers residing at each elevation serviced by the two tanks.

		25	80000	Sub Pump (gal)	sum of need	pump accum	difference	GPM	23625	Pump 1 (gal)	sum of need	pump accum	difference	GPM	11375	Pump 3 (gal)	sum of need	pump accum	difference	GPM
			Submerrsible Tank						TANK 1						TANK 3					
0	0%	0	**0**	3636	0	0	0	61	**0**	1074	0	0	0	18	**0**	517	0	0	0	9
1	0%	0	**0**	3636	0	7273	7273	61	**0**	1074	0	2148	2148	18	**0**	517	0	7513	7513	9
2	0%	0	**0**	3636	0	10909	10909	61	**0**	1074	0	3222	3222	18	**0**	517	0	15565	15565	9
3	0%	0	**0**	3636	0	14545	14545	61	**0**	1074	0	4295	4295	18	**0**	517	0	25765	25765	9
4	0%	0	**0**	3636	0	18182	18182	61	**0**	1074	0	5369	5369	18	**0**	517	0	38112	38112	9
5	0%	0	**0**	3636	0	21818	21818	61	**0**	1074	0	6443	6443	18	**0**	517	0	52607	52607	9
6	3%	0.75	**2400**	3636	2400	25455	23055	61	**709**	1074	709	7517	6808	18	**341**	517	341	3619	3278	9
7	3%	0.75	**2400**	0	4800	25455	20655	0	**709**		1418	7517	6100	0	**341**		683	3619	2937	0
8	4%	1	**3200**	0	8000	25455	17455	0	**945**		2363	7517	5155	0	**455**		1138	3619	2482	0
9	7%	1.75	**5600**	3636	13600	29091	15491	61	**1654**	1074	4016	8591	4575	18	**796**	517	1934	4136	2203	9
10	7%	1.75	**5600**	3636	19200	32727	13527	61	**1654**	1074	5670	9665	3995	18	**796**	517	2730	4653	1923	9
11	7%	1.75	**5600**	3636	24800	36364	11564	61	**1654**	1074	7324	10739	3415	18	**796**	517	3526	5170	1644	9
12	7%	1.75	**5600**	3636	30400	40000	9600	61	**1654**	1074	8978	11813	2835	18	**796**	517	4323	5688	1365	9
13	5%	1.25	**4000**	3636	34400	43636	9236	61	**1181**	1074	10159	12886	2728	18	**569**	517	4891	6205	1313	9
14	5%	1.25	**4000**	3636	38400	47273	8873	61	**1181**	1074	11340	13960	2620	18	**569**	517	5460	6722	1262	9
15	5%	1.25	**4000**	3636	42400	50909	8509	61	**1181**	1074	12521	15034	2513	18	**569**	517	6029	7239	1210	9
16	5%	1.25	**4000**	3636	46400	54545	8145	61	**1181**	1074	13703	16108	2405	18	**569**	517	6598	7756	1158	9
17	9%	2.25	**7200**	3636	53600	58182	4582	61	**2126**	1074	15829	17182	1353	18	**1024**	517	7621	8273	651	9
18	9%	2.25	**7200**	3636	60800	61818	1018	61	**2126**	1074	17955	18256	301	18	**1024**	517	8645	8790	145	9
19	9%	2.25	**7200**	3636	68000	65455	-2545	61	**2126**	1074	20081	19330	-752	18	**1024**	517	9669	9307	-362	9
20	9%	2.25	**7200**	3636	75200	69091	-6109	61	**2126**	1074	22208	20403	-1804	18	**1024**	517	10693	9824	-869	9
21	3%	0.75	**2400**	3636	77600	72727	-4873	61	**709**	1074	22916	21477	-1439	18	**341**	517	11034	10341	-693	9
22	3%	0.75	**2400**	3636	80000	76364	-3636	61	**709**	1074	23625	22551	-1074	18	**341**	517	11375	10858	-517	9
23	0%	0	**0**	3636	80000	80000	0	61	**0**					0	**0**					0

22	Pump Hours Used	Pump	**GPM**	**GPH**	Day Be	Hours of Pumping	Min Tank Vol (Gal)
		New	60.61	3636	6109	2	23054.55
		1	17.90	1074	1804	0	
		3	8.62	517	869	0	

Table A7. Scenario 3 for the pump schedule in Las Delicias, El Salvador. This scenario outlines the least number of PV modules but the maximum energy storage and battery number as near continuous (22 hours) of pumping is scheduled.

				Submerrsible Tank								TANK 1							TANK 3				
Hour		25	80000	Sub Pump (gal)	sum of need	pump accum	difference	Tank Height (ft)	GPM	23625	Pump 1 (gal)	sum of need	pump accum	difference	Tank Height (ft)	GPM	11375	Pump 3 (gal)	sum of need	pump accum	difference	Tank Height (ft)	GPM
0	0%	0	**0**	8000	0		0	0.00		**0**			0	0	0.00		**0**		0	0	0	0.00	
1	0%	0	**0**		0	8000	8000	13.62		**0**		0	0	0	0.00		**0**		0	0	0	0.00	
2	0%	0	**0**		0	8000	8000	13.62		**0**		0	0	0	0.00		**0**		0	0	0	0.00	
3	0%	0	**0**		0	8000	8000	13.62		**0**		0	0	0	0.00		**0**		0	0	0	0.00	
4	0%	0	**0**		0	8000	8000	13.62		**0**		0	0	0	0.00		**0**		0	0	0	0.00	
5	0%	0	**0**		0	8000	8000	13.62		**0**		0	0	0	0.00		**0**		0	0	0	0.00	
6	3%	0.75	**2400**		2400	8000	5600	9.53		**709**		709	0	-709	-1.21		**341**		341	0	-341	-0.58	
7	3%	0.75	**2400**	0	4800	8000	3200	5.45		**709**		1418	0	-1418	-2.41		**341**		683	0	-683	-1.16	
8	4%	1	**3200**	0	8000	8000	0	0.00		**945**		2363	0	-2363	-4.02		**455**		1138	0	-1138	-1.94	
9	7%	1.75	**5600**	6349	13600	14349	749	1.28	106	**1654**	1875	4016	1875	-2141	-3.64	31	**796**	903	1934	903	-1031	-1.75	15
10	7%	1.75	**5600**	6349	19200	20698	1498	2.55	106	**1654**	1875	5670	3750	-1920	-3.27	31	**796**	903	2730	1806	-924	-1.57	15
11	7%	1.75	**5600**	6349	24800	27048	2248	3.83	106	**1654**	1875	7324	5625	-1699	-2.89	31	**796**	903	3526	2708	-818	-1.39	15
12	7%	1.75	**5600**	6349	30400	33397	2997	5.10	106	**1654**	1875	8978	7500	-1478	-2.51	31	**796**	903	4323	3611	-711	-1.21	15
13	5%	1.25	**4000**	6349	34400	39746	5346	9.10	106	**1181**	1875	10159	9375	-784	-1.33	31	**569**	903	4891	4514	-377	-0.64	15
14	5%	1.25	**4000**	6349	38400	46095	7695	13.10	106	**1181**	1875	11340	11250	-90	-0.15	31	**569**	903	5460	5417	-43	-0.07	15
15	5%	1.25	**4000**	6349	42400	52444	10044	17.10	106	**1181**	1875	12521	13125	604	1.03	31	**569**	903	6029	6319	291	0.49	15
16	5%	1.25	**4000**	6349	46400	58794	12394	21.09	106	**1181**	1875	13703	15000	1298	2.21	31	**569**	903	6598	7222	625	1.06	15
17	9%	2.25	**7200**	6349	53600	65143	11543	19.65	106	**2126**	1875	15829	16875	1046	1.78	31	**1024**	903	7621	8125	504	0.86	15
18	9%	2.25	**7200**	6349	60800	71492	10692	18.20	106	**2126**	1875	17955	18750	795	1.35		**1024**	903	8645	9028	383	0.65	
19	9%	2.25	**7200**	6349	68000	77841	9841	16.75	106	**2126**	1875	20081	20625	544	0.93		**1024**	903	9669	9931	262	0.45	
20	9%	2.25	**7200**	6349	75200	84190	8990	15.30	106	**2126**	1875	22208	22500	293	0.50		**1024**	903	10693	10833	141	0.24	
21	3%	0.75	**2400**	3810	77600	88000	10400	17.70	63	**709**	1125	22916	23625	709	1.21		**341**	542	11034	11375	341	0.58	
22	3%	0.75	**2400**		80000	88000	8000	13.62		**709**		23625	23625	0	0.00		**341**		11375	11375	0	0.00	
23	0%	0	**0**		80000	88000	8000	13.62		**0**					0.00		**0**					0.00	

		Pump	GPM	kW	kWH	GPH	Day Before	Hours of Pumping	Min Tank Vol (Gal)
12.6	Pump Hours Used								
10	Tank Diameter (ft)	New	105.82	18.75	236.25	6349	0	0.00	12393.65
78.5	Tank Area (ft^2)	1	31.25	5.63	70.88	1875	2363	0.37	
		3	15.05	1.13	14.18	903	1138	0.18	
				25.50	321.30				

Table A8. Scenario 2 for the pump schedule in Las Delicias, El Salvador. This scenario is a result of the iterative method of solving for optimal pumping. 12.6 hours of pumping are scheduled and this scenario minimizes the energy waste caused by the system.

Table A9. Table of different scenarios considered for pumping detailed in pump schedule. Modules required are calculated with equations 1 and 2.
Scenario 1 was chosen as the optimal pumping scenario.

Month	10	10	10
Scenario	**2**	**1**	**3**
kW Required	40.00	15.23	25.50
kWh	360.00	335.06	321.30
Hours Pumping/Day	9	22	12.6
9am-12pm	0.54	0.54	0.54
12pm-3pm	0.75	0.75	0.75
3pm-6pm	0.41	0.41	0.41
Modules Required to run Pump	40.18	15.30	25.61
Modules Required to run Pump (rounded)	41.00	27.00	26.00
Output (kWh/Day)	507.74	334.36	321.98
Pump Use (kWh/Day)	360.00	137.07	229.50
Excess/Battery Storage (kWh/Day)	147.74	197.29	92.48
Pump Use supplied w/ Sun (Hours/Day)	9.00	9.00	9.00
Pump Use Needed (Hr/Day)	0.00	13.00	3.60
Excess Storage (kWh/Day)	147.74	197.29	92.48
Battery Use (kWh/Day)	0	197.99	91.80
Energy Waste (kWh/Day)	147.74	-0.70	0.68
Batteries Needed (#)	0	16	8
Pump Hours Extra	3.69	-0.05	0.03
Land Area Required (m^2)	52.34	34.47	33.19

Table A10. Table of Monthly Averaged Insolation Incident on a Horizontal Surfaced at indicated times in kW/m^2. These numbers were used to calculate the minimum number of modules needed to power the pumps year round.

Monthly Averaged Insolation Incident On A Horizontal Surface At Indicated GMT Times (kW/m^2)												
Las Delicias	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
9am-12pm	0.5	0.54	0.57	0.59	0.53	0.53	0.55	0.56	0.52	0.54	0.55	0.51
12pm-3pm	0.8	0.87	0.89	0.85	0.76	0.76	0.79	0.8	0.71	0.75	0.77	0.77
3pm-6pm	0.53	0.6	0.61	0.57	0.51	0.51	0.54	0.53	0.42	0.41	0.43	0.46
Modules	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00
Power Provided (kWh/Day)	346.60	380.69	392.06	380.69	340.92	340.92	356.07	357.97	312.51	321.98	331.45	329.56
Required	321.30	321.30	321.30	321.30	321.30	321.30	321.30	321.30	321.30	321.30	321.30	321.30
Excess	25.30	59.39	70.76	59.39	19.62	19.62	34.77	36.67	-8.79	0.68	10.15	8.26

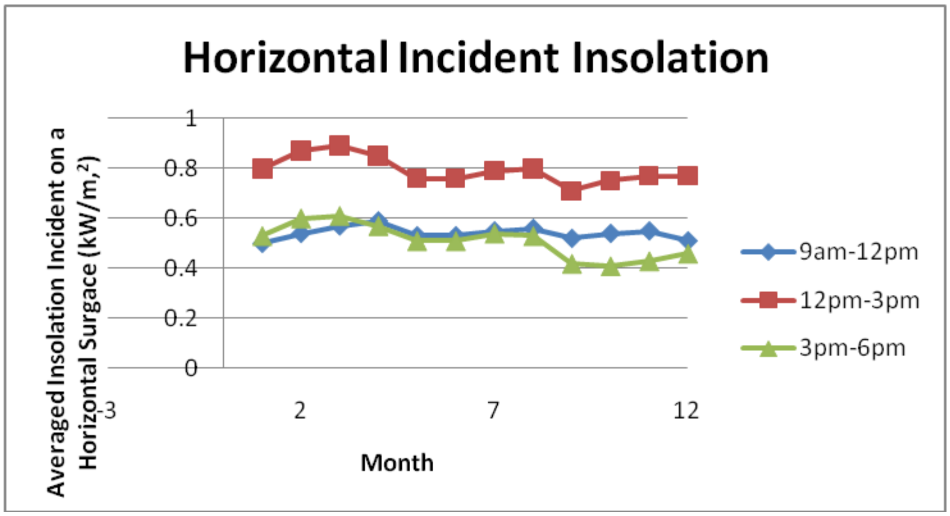


Figure A11. Graph of Monthly Averaged Insolation Incident on a Horizontal Surface over different months of the year at different times. The data was retrieved from the NASA Atmospheric Science Data Center and represents averages over the past 22 years.

Table A12. Table of all photovoltaic options considered. The max power represents the maximum power of each panel tested at Standard Test Conditions (STC), 1.5 atm, 1000 W/m^2, and 25°C.

Type	Max Power (Wp)	Efficiency	Module Area (m^2)	Panels/Module
mono	180	17.00%	1.28	72
mono	185	17.50%	1.28	72
mono	190	17.75%	1.28	72
poly	200	15.25%	1.48	54
poly	210	16.00%	1.48	54
poly	220	15.50%	1.66	60
poly	230	16.20%	1.66	60
poly	240	17.00%	1.66	60
CPV	600	23.00%	3.43	1
CPV	2400	23.00%	13.73	1

					Submerrsible Tank								
		30	22500	Sub Pump (gal)	sum of need	pump accum	difference	GPM					
0	0%	0	**0**		0	0	0						
1	0%	0	**0**		0	0	0						
2	0%	0	**0**		0	0	0						
3	0%	0	**0**		0	0	0						
4	0%	0	**0**		0	0	0						
5	0%	0	**0**		0	0	0						
6	3%	0.75	**675**		675	0	-675						
7	3%	0.75	**675**	0	1350	0	-1350						
8	4%	1	**900**	0	2250	0	-2250						
9	7%	1.75	**1575**	2500	3825	2500	-1325	42					
10	7%	1.75	**1575**	2500	5400	5000	-400	42		Residents			
11	7%	1.75	**1575**	2500	6975	7500	525	42		750			
12	7%	1.75	**1575**	2500	8550	10000	1450	42					
13	5%	1.25	**1125**	2500	9675	12500	2825	42					
14	5%	1.25	**1125**	2500	10800	15000	4200	42					
15	5%	1.25	**1125**	2500	11925	17500	5575	42					
16	5%	1.25	**1125**	2500	13050	20000	6950	42					
17	9%	2.25	**2025**	2500	15075	22500	7425	42					
18	9%	2.25	**2025**		17100	22500	5400						
19	9%	2.25	**2025**		19125	22500	3375						
20	9%	2.25	**2025**		21150	22500	1350						
21	3%	0.75	**675**		21825	22500	675						
22	3%	0.75	**675**		22500	22500	0						
23	0%	0	**0**		22500	22500	0						
	9	Pump Hours Used			Pump	**GPM**	**kW**	**kWH**	**GPH**	Day Before	Hours of Pumping	Min Tank Vol (Gal)	Max Tank Vol
					New	41.67	4.02	198.02	2500	2250	0.90	2250.00	

Table A13: Scenario 1 for the pumping schedule in Apatut, the Philippines. This scenario relates to the maximum number of solar panels as only 9 hours of pumping is scheduled but no batteries are required.

				Submerrsible Tank									
		30	22500	Sub Pump (gal)	sum of need	pump accum	difference	GPM					
0	0%	0	**0**	1023	0	0	0	17					
1	0%	0	**0**	1023	0	2045	2045	17					
2	0%	0	**0**	1023	0	3068	3068	17					
3	0%	0	**0**	1023	0	4091	4091	17					
4	0%	0	**0**	1023	0	5114	5114	17					
5	0%	0	**0**	1023	0	6136	6136	17					
6	3%	0.75	**675**	1023	675	7159	6484	17					
7	3%	0.75	**675**	0	1350	7159	5809						
8	4%	1	**900**	0	2250	7159	4909						
9	7%	1.75	**1575**	1023	3825	8182	4357	17					
10	7%	1.75	**1575**	1023	5400	9205	3805	17		Residents			
11	7%	1.75	**1575**	1023	6975	10227	3252	17		750			
12	7%	1.75	**1575**	1023	8550	11250	2700	17					
13	5%	1.25	**1125**	1023	9675	12273	2598	17					
14	5%	1.25	**1125**	1023	10800	13295	2495	17					
15	5%	1.25	**1125**	1023	11925	14318	2393	17					
16	5%	1.25	**1125**	1023	13050	15341	2291	17					
17	9%	2.25	**2025**	1023	15075	16364	1289	17					
18	9%	2.25	**2025**	1023	17100	17386	286	17					
19	9%	2.25	**2025**	1023	19125	18409	-716	17					
20	9%	2.25	**2025**	1023	21150	19432	-1718	17					
21	3%	0.75	**675**	1023	21825	20455	-1370	17					
22	3%	0.75	**675**	1023	22500	21477	-1023	17					
23	0%	0	**0**	1023	22500	22500	0	17					
	22	Pump Hours Used			Pump	**GPM**	**kW**	**kWH**	**GPH**	Day Before	Hours of Pumping	Min Tank Vol (Gal)	Max Tank Vol
					New	17.05	2.01	198.02	1023	1718	1.68	1718.18	

Table A14: Scenario 3 for the pump schedule in Apatut, the Philippines. This scenario outlines the least number of PV modules but the maximum energy storage and battery number as near continuous (22 hours) of pumping is scheduled.

Month	Jan	Jan
Scenario	**1**	**2**
kW Required	4.02	2.01
kWh	36.18	44.16
Hours Pumping/Day	9	22
9am-12pm	0.22	0.22
12pm-3pm	0.7	0.7
3pm-6pm	0.64	0.64
Modules Required to run Pump	7.53	3.76
Modules Required to run Pump (rounded)	8	4
Output (kWh/Day)	90.91	45.46
Pump Use (kWh/Day)	36.18	18.07
Excess/Battery Storage (kWh/Day)	54.73	27.39
Pump Use supplied w/ Sun (Hours/Day)	9	9
Pump Use Needed (Hr/Day)	0	13
Excess Storage (kWh/Day)	54.73	27.39
Battery Use (kWh/Day)	0.00	26.09
Energy Waste (kWh/Day)	54.73	1.30
Batteries Needed (#)	0.00	3.00
Pump Hours Extra	13.61	0.65
Land Area Required (m^2)	10.2128	5.1064

Table A15: Table of different scenarios considered for pumping detailed in pump schedule. Modules required is calculated with equations 1 and 2. Scenario 1 was chosen as the optimal pumping scenario.

Table A16 Data used for TDH calculations in Apatut, the Philippines.

Pipe type	**L**	**(L/D)**	**D**		**A**
	[m]	-	[in]	[m]	[m^2]
Drop pipe	28	-	4	0.1016	0.0081073
Section 1	20	-	4	0.1016	0.0081073
Section 2	60	-	4	0.1016	0.0081073
Section 3	3	-	4	0.1016	0.0081073
Standard 90 elbow	-	30	-	-	-

Table A17 Data for Apatut, the Philippines. Three 90 degree elbows were used in calculations. The head loss associated with them is lumped into one cell unit.

Q	u	Re	f_F	Head Loss					Static Height	TOTAL	Pump	
				Drop pipe	Section 1	Section 2	Section 3	3 - 90 elbows		TDH		
[gpm]	[m/s]	-	-	[ft]	[ft]	[ft]	[ft]	[ft]	[ft]	[ft]	[hp]	[kW]
10	0.078	7886	0.008222	0.009	0.007	0.020	0.001	0.0030	289	289	1.34	1
20	0.156	15773	0.006889	0.031	0.022	0.066	0.003	0.0100	289	289.1	2.68	2.01
30	0.233	23659	0.006247	0.063	0.045	0.135	0.007	0.0205	289	289.3	4.02	3.01
40	0.3111	31545	0.005842	0.104	0.075	0.224	0.011	0.0341	289	289.4	5.36	4.02
50	0.389	39431	0.005554	0.155	0.111	0.332	0.017	0.0506	289	289.6	6.7	5.03
60	0.467	47318	0.005333	0.214	0.153	0.459	0.023	0.0700	289	289.9	8.05	6.04
70	0.544	55204	0.005156	0.282	0.202	0.605	0.030	0.0921	289	290.2	9.4	7.05
80	0.622	63090	0.00501	0.358	0.256	0.767	0.038	0.1169	289	290.5	10.76	8.07
90	0.700	70976	0.004886	0.442	0.316	0.947	0.047	0.1443	289	290.9	12.12	9.09
100	0.778	78863	0.004779	0.534	0.381	1.143	0.057	0.1743	289	291.3	13.48	10.11
110	0.856	86749	0.004685	0.633	0.452	1.356	0.068	0.2067	289	291.7	14.85	11.14
120	0.933	94635	0.004602	0.740	0.529	1.586	0.079	0.2416	289	292.2	16.23	12.17
130	1.011	102522	0.004527	0.854	0.610	1.831	0.092	0.279	289	292.6	17.61	13.21
140	1.089	110408	0.004459	0.976	0.697	2.091	0.105	0.3187	289	293.2	19	14.25
150	1.167	118294	0.004398	1.105	0.789	2.368	0.118	0.3608	289	293.7	20.4	15.3
160	1.244	126180	0.004341	1.241	0.886	2.659	0.133	0.4053	289	294.3	21.8	16.35
170	1.322	134067	0.004289	1.384	0.989	2.966	0.148	0.452	289	294.9	23.21	17.41
180	1.4	141953	0.004241	1.534	1.096	3.288	0.1644	0.5011	289	295.6	24.63	18.47
190	1.478	149839	0.004197	1.692	1.208	3.625	0.1812	0.5524	289	296.2	26.06	19.54
200	1.556	157726	0.004155	1.856	1.325	3.976	0.1988	0.606	289	296.9	27.49	20.62
210	1.633	165612	0.004116	2.027	1.448	4.343	0.2171	0.6618	289	297.7	28.94	21.71
220	1.711	173498	0.004079	2.204	1.574	4.723	0.2362	0.7199	289	298.4	30.4	22.8
230	1.789	181384	0.004044	2.389	1.706	5.119	0.2559	0.7801	289	299.2	31.86	23.9
240	1.867	189271	0.004011	2.58	1.843	5.528	0.2764	0.8425	289	300.1	33.34	25
250	1.944	197157	0.00398	2.778	1.984	5.952	0.2976	0.9071	289	300.9	34.83	26.12
260	2.022	205043	0.003951	2.982	2.13	6.39	0.3195	0.9739	289	301.8	36.32	27.24
270	2.1	212929	0.003923	3.193	2.281	6.842	0.3421	1.043	289	302.7	37.84	28.38
280	2.178	220816	0.003896	3.411	2.436	7.308	0.3654	1.114	289	303.6	39.36	29.52
290	2.256	228702	0.00387	3.635	2.596	7.788	0.3894	1.187	289	304.6	40.89	30.67
300	2.333	236588	0.003846	3.865	2.761	8.282	0.4141	1.262	289	305.6	42.44	31.83

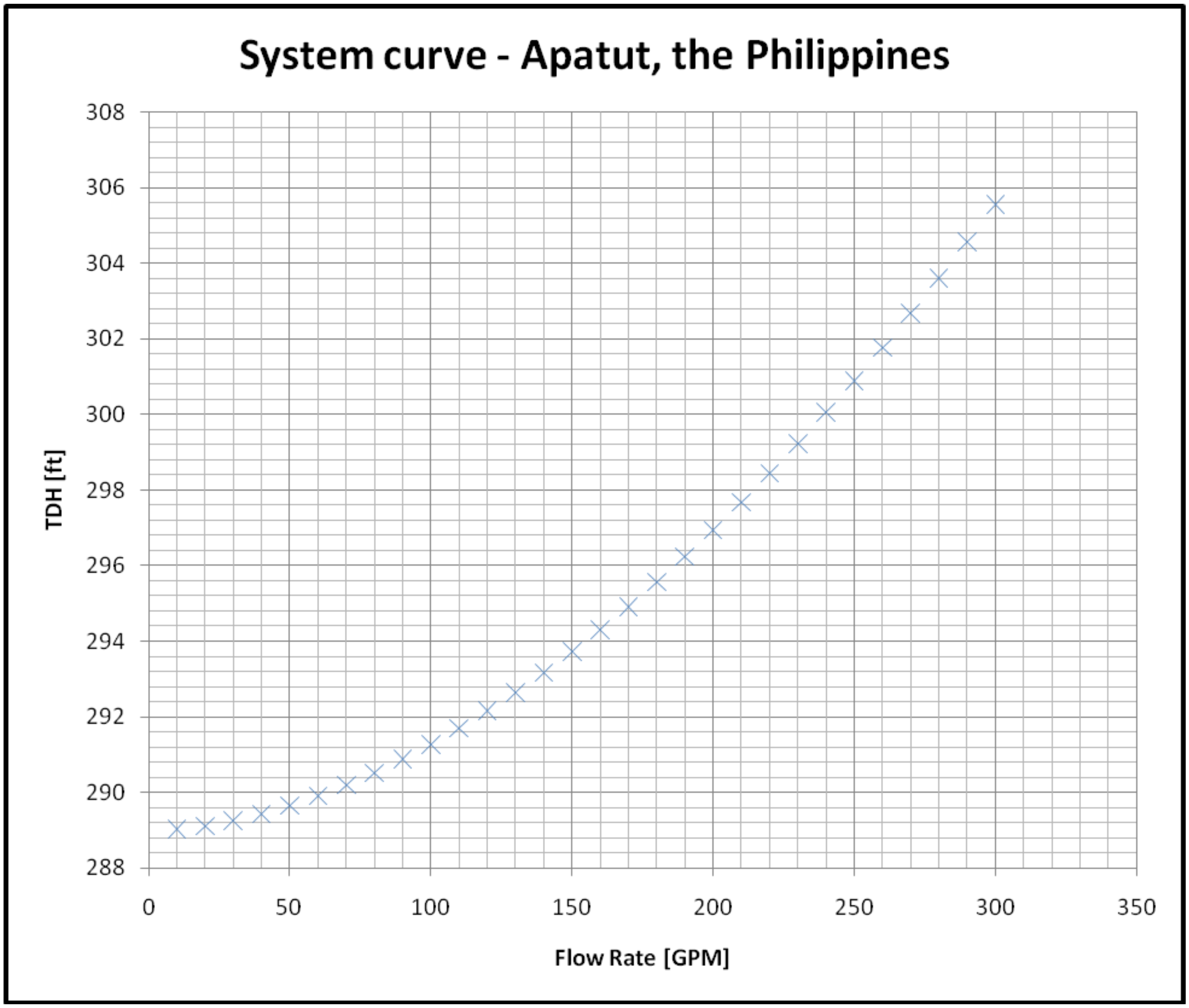


Figure A18 A system curve for Apatut, the Philippines.

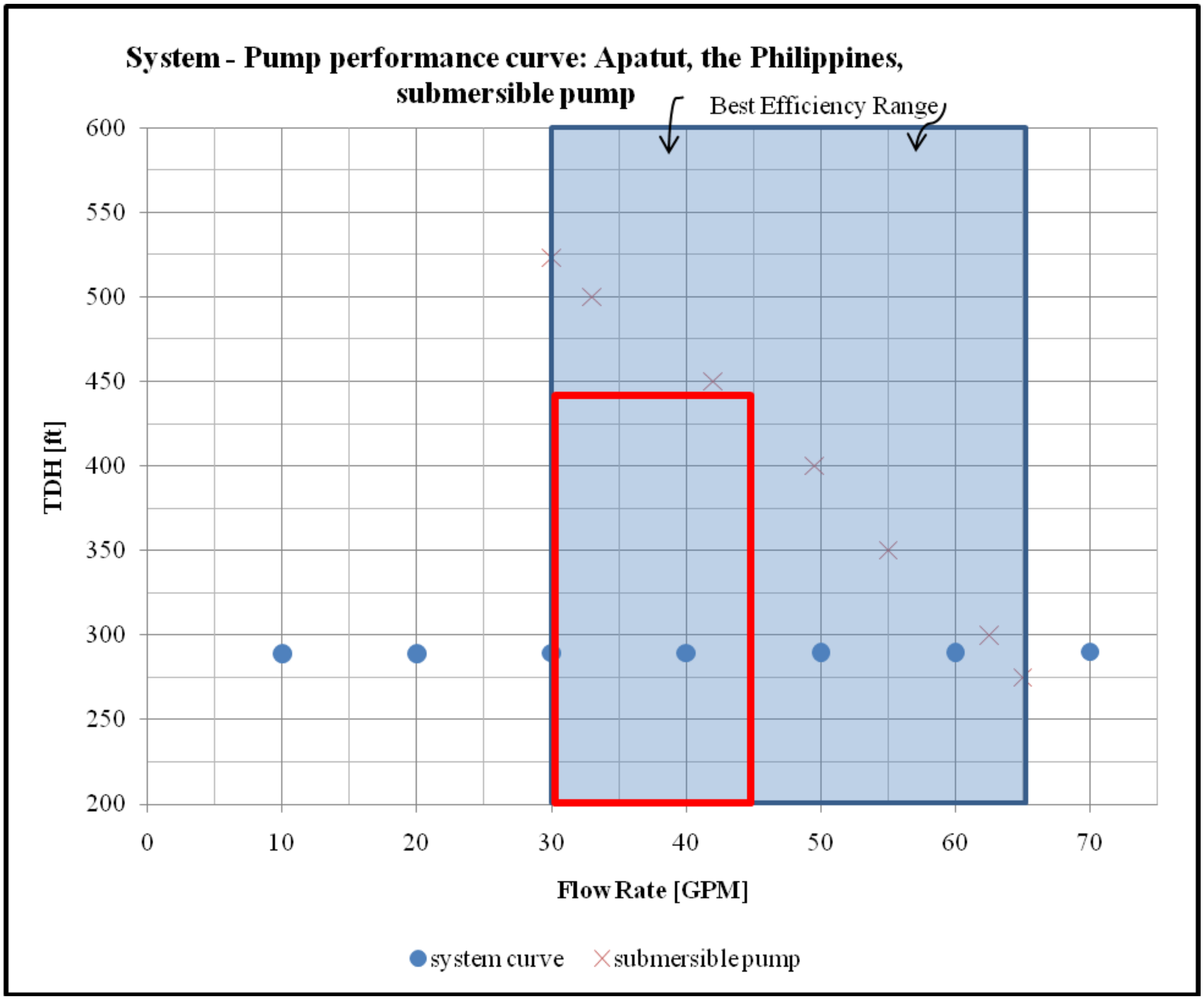


Figure A19 System – Pump performance curve for Apatut, the Philippines.

Table A20 Data for Apatut, the Philippines. 3, 90 degree elbow fittings were included in the system calculations.

Q	u	Re	f_r	Head Loss					Static Height	TOTAL	Pump	
				Drop pipe	Section 1	Section 2	Section 3	3 - 90 elbows		TDH		
[gpm]	[m/s]	-	-	[ft]	[ft]	[ft]	[ft]	[ft]	[ft]	[ft]	[hp]	[kW]
10	0.07777	7886	0.008222	0.009181	0.006558	0.01967	0.000984	0.002998	289	289	1.34	1
20	0.1555	15773	0.006889	0.03076	0.02197	0.06593	0.003296	0.01004	289	289.1	2.68	2.01
30	0.2333	23659	0.006247	0.06278	0.04484	0.1345	0.006726	0.0205	289	289.3	4.02	3.01
40	0.3111	31545	0.005842	0.1044	0.07455	0.2236	0.01118	0.03408	289	289.4	5.36	4.02
50	0.3889	39431	0.005554	0.155	0.1107	0.3322	0.01661	0.05063	289	289.6	6.70	5.03
60	0.4667	47318	0.005333	0.2144	0.1531	0.4593	0.02297	0.07001	289	289.9	8.05	6.04
70	0.5444	55204	0.005156	0.2821	0.2015	0.6045	0.03023	0.09213	289	290.2	9.40	7.05
80	0.6222	63090	0.00501	0.358	0.2557	0.76722	0.03836	0.1169	289	290.5	10.76	8.07
90	0.7000	70976	0.004886	0.4419	0.3157	0.947	0.04735	0.1443	289	290.9	12.12	9.09
100	0.7778	78863	0.004779	0.5336	0.3812	1.143	0.05717	0.1743	289	291.3	13.48	10.11
110	0.8555	86749	0.004685	0.633	0.4521	1.356	0.06782	0.2067	289	291.7	14.85	11.14
120	0.9333	94635	0.004602	0.7399	0.5285	1.586	0.07928	0.2416	289	292.2	16.23	12.17
130	1.011	102522	0.004527	0.8543	0.6102	1.831	0.09153	0.279	289	292.6	17.61	13.21
140	1.089	110408	0.004459	0.976	0.6971	2.091	0.1046	0.3187	289	293.2	19.00	14.25
150	1.167	118294	0.004398	1.105	0.7892	2.368	0.1184	0.3608	289	293.7	20.4	15.3
160	1.244	126180	0.004341	1.241	0.8864	2.659	0.133	0.4053	289	294.3	21.8	16.35
170	1.322	134067	0.004289	1.384	0.9887	2.966	0.1483	0.452	289	294.9	23.21	17.41
180	1.400	141953	0.004241	1.534	1.096	3.288	0.1644	0.5011	289	295.6	24.63	18.47
190	1.478	149839	0.004197	1.692	1.208	3.625	0.1812	0.5524	289	296.2	26.06	19.54
200	1.556	157726	0.004155	1.856	1.325	3.976	0.1988	0.606	289	296.9	27.49	20.62
210	1.633	165612	0.004116	2.027	1.448	4.343	0.2171	0.6618	289	297.7	28.94	21.71
220	1.711	173498	0.004079	2.204	1.574	4.723	0.2362	0.7199	289	298.4	30.4	22.8
230	1.789	181384	0.004044	2.389	1.706	5.119	0.2559	0.7801	289	299.2	31.86	23.9
240	1.867	189271	0.004011	2.58	1.843	5.528	0.2764	0.8425	289	300.1	33.34	25
250	1.944	197157	0.00398	2.778	1.984	5.952	0.2976	0.9071	289	300.9	34.83	26.12
260	2.022	205043	0.003951	2.982	2.13	6.39	0.3195	0.9739	289	301.8	36.32	27.24
270	2.1	212929	0.003923	3.193	2.281	6.842	0.3421	1.043	289	302.7	37.84	28.38
280	2.178	220816	0.003896	3.411	2.436	7.308	0.3654	1.114	289	303.6	39.36	29.52
290	2.256	228702	0.00387	3.635	2.596	7.788	0.3894	1.187	289	304.6	40.89	30.67
300	2.333	236588	0.003846	3.865	2.761	8.282	0.4141	1.262	289	305.6	42.44	31.83

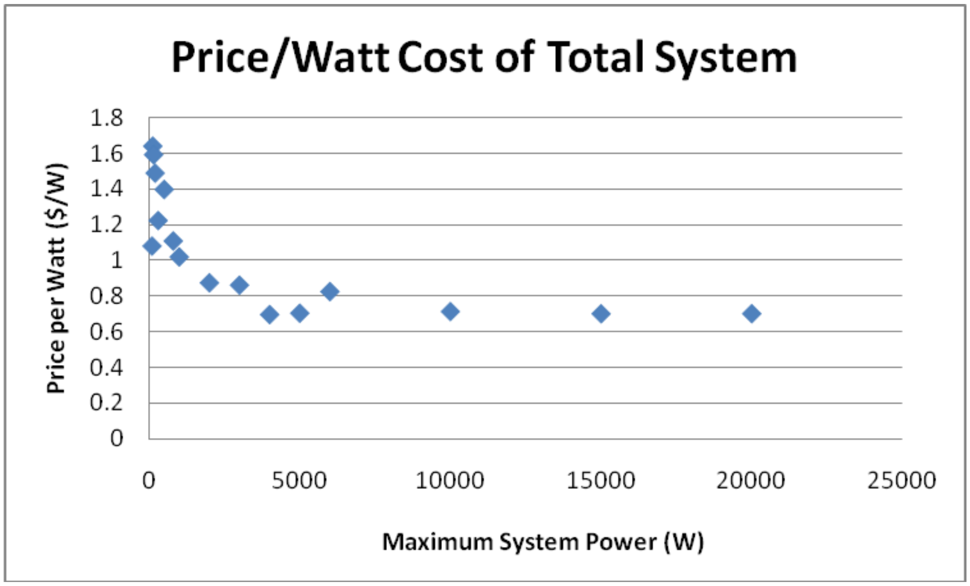


Figure A21: Graph of the price per watt of the entire system (not including batteries) and the maximum power of the system. From here, and estimate of $0.65/W was determined due to economies of scale related to the larger 63,000 W maximum power system. This data is also used to calculate the cost for the Philippines power system.

Monthly Averaged Insolation Incident On A Horizontal Surface At Indicated GMT Times (kW/m^2)												
Apatut	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
9am-12pm	0.22	0.25	0.34	0.41	0.39	0.35	0.31	0.27	0.31	0.33	0.28	0.24
12pm-3pm	0.7	0.76	0.84	0.89	0.78	0.71	0.67	0.61	0.67	0.7	0.68	0.66
3pm-6pm	0.64	0.71	0.79	0.82	0.66	0.6	0.56	0.56	0.57	0.56	0.55	0.56
6pm-9pm	-	0.17	0.2	0.2	0.17	0.15	0.13	0.13	0.1	-	-	-
Modules	8	8	8	8	8	8	8	8	8	8	8	8
Power Provided (kWh/Day)	90.91	110.14	126.46	135.20	116.55	105.48	97.32	91.49	96.16	92.66	88.00	85.08
Required	36.18	36.18	36.18	36.18	36.18	36.18	36.18	36.18	36.18	36.18	36.18	36.18
Excess	54.73	73.96	90.28	99.02	80.37	69.30	61.14	55.31	59.98	56.48	51.82	48.90

Table A22: Table of Monthly Averaged Insolation Incident on a Horizontal Surfaced at indicated times in kW/m^2. These numbers were used to calculate the minimum number of modules needed to power the pumps year round.

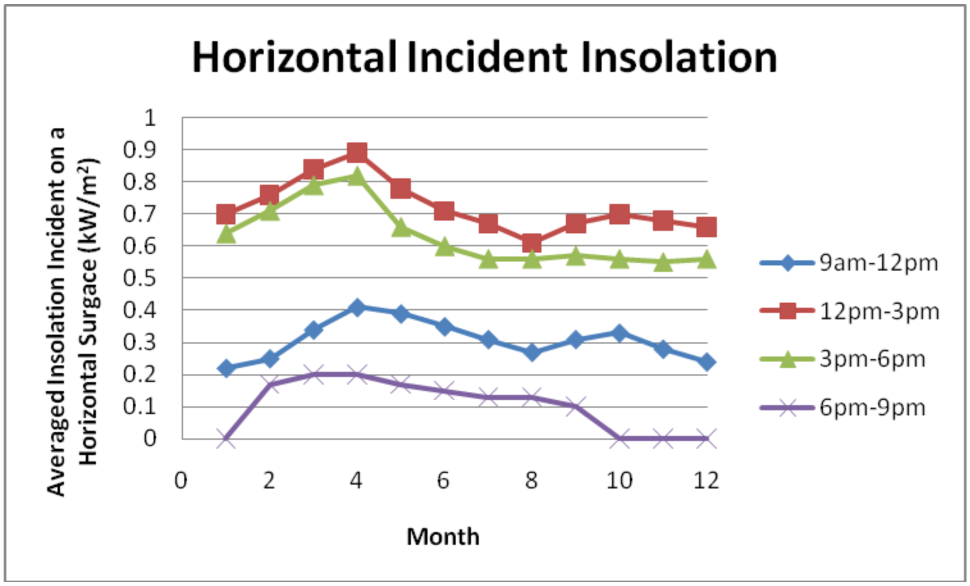
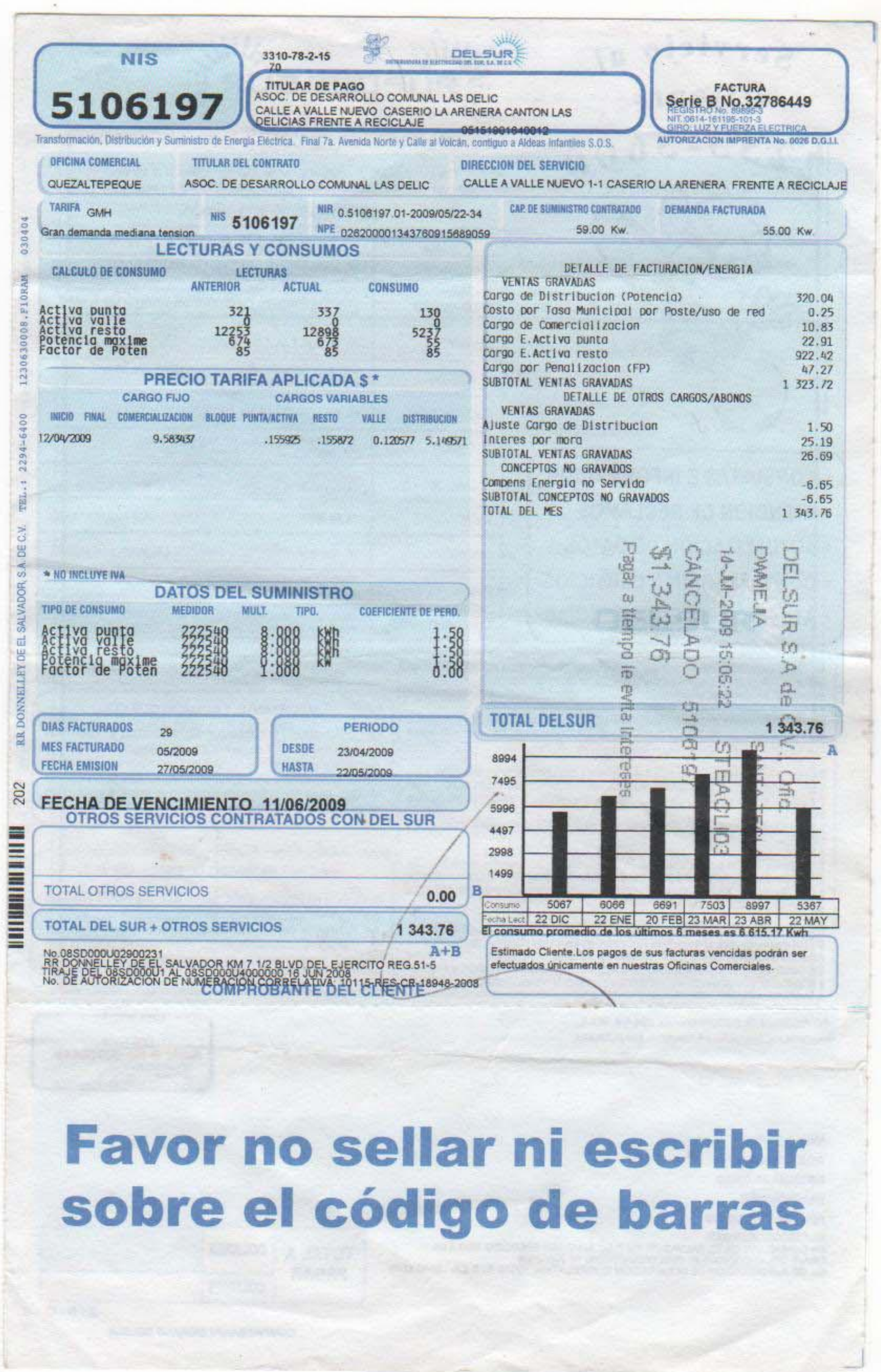


Figure A23: Graph of Monthly Averaged Insolation Incident on a Horizontal Surface over different months of the year at different times. The data was retrieved from the NASA Atmospheric Science Data Center and represents averages over the past 22 years.



NIS 5106197

3310-78-2-15
70

DELSUR

TITULAR DE PAGO
ASOC. DE DESARROLLO COMUNAL LAS DELIC
CALLE A VALLE NUEVO CASERIO LA ARENERA CANTON LAS DELICIAS FRENTE A RECICLAJE
05151001640012

FACTURA
Serie B No.32786449
REGISTRO No. 89895-3
NIT 0614-161195-101-3
GIRO: LUZ Y FUERZA ELECTRICA
AUTORIZACION IMPRENTA No. 0026 D.G.I.I.

Transformación, Distribución y Suministro de Energía Eléctrica. Final 7a. Avenida Norte y Calle al Volcán, contiguo a Aldeas Infantiles S.O.S.

OFICINA COMERCIAL	TITULAR DEL CONTRATO	DIRECCION DEL SERVICIO
QUEZALTEPEQUE	ASOC. DE DESARROLLO COMUNAL LAS DELIC	CALLE A VALLE NUEVO 1-1 CASERIO LA ARENERA FRENTE A RECICLAJE

TARIFA GMH — Gran demanda mediana tension
NIS 5106197
NIR 0.5106197.01-2009/05/22-34
NPE 026200001343760915689059
CAP. DE SUMINISTRO CONTRATADO 59.00 Kw.
DEMANDA FACTURADA 55.00 Kw.

LECTURAS Y CONSUMOS

CALCULO DE CONSUMO	LECTURAS ANTERIOR	LECTURAS ACTUAL	CONSUMO
Activa punta	321	337	130
Activa valle	0	0	0
Activa resto	12253	12898	5237
Potencia maxime	674	673	55
Factor de Poten	85	85	85

PRECIO TARIFA APLICADA $ *

INICIO	FINAL	CARGO FIJO COMERCIALIZACION	BLOQUE	PUNTA/ACTIVA	RESTO	VALLE	DISTRIBUCION
12/04/2009		9.583437		.155925	.155872	0.120577	5.149571

* NO INCLUYE IVA

DETALLE DE FACTURACION/ENERGIA

VENTAS GRAVADAS	
Cargo de Distribucion (Potencia)	320.04
Costo por Tasa Municipal por Poste/uso de red	0.25
Cargo de Comercializacion	10.83
Cargo E.Activa punta	22.91
Cargo E.Activa resto	922.42
Cargo por Penalizacion (FP)	47.27
SUBTOTAL VENTAS GRAVADAS	1 323.72
DETALLE DE OTROS CARGOS/ABONOS	
VENTAS GRAVADAS	
Ajuste Cargo de Distribucion	1.50
Interes por mora	25.19
SUBTOTAL VENTAS GRAVADAS	26.69
CONCEPTOS NO GRAVADOS	
Compens Energia no Servida	-6.65
SUBTOTAL CONCEPTOS NO GRAVADOS	-6.65
TOTAL DEL MES	1 343.76

DELSUR S.A de C.V., Ofic
DWMEJA
14-JUN-2009 15:05:22
CANCELADO 5106197
$1,343.76
STEACLI03
Pagar a tiempo le evita intereses

DATOS DEL SUMINISTRO

TIPO DE CONSUMO	MEDIDOR	MULT.	TIPO.	COEFICIENTE DE PERD.
Activa punta	222540	8.000	kWh	1.50
Activa valle	222540	8.000	kWh	1.50
Activa resto	222540	8.000	kWh	1.50
Potencia maxime	222540	0.080	KW	1.50
Factor de Poten	222540	1.000		0.00

DIAS FACTURADOS 29
MES FACTURADO 05/2009
FECHA EMISION 27/05/2009

PERIODO
DESDE 23/04/2009
HASTA 22/05/2009

TOTAL DELSUR 1 343.76 A

Consumo	5067	6066	6691	7503	8997	5367
Fecha Lect	22 DIC	22 ENE	20 FEB	23 MAR	23 ABR	22 MAY

El consumo promedio de los ultimos 6 meses es 6 615.17 Kwh

FECHA DE VENCIMIENTO 11/06/2009

OTROS SERVICIOS CONTRATADOS CON DEL SUR

TOTAL OTROS SERVICIOS 0.00 B

TOTAL DEL SUR + OTROS SERVICIOS 1 343.76 A+B

Estimado Cliente.Los pagos de sus facturas vencidas podrán ser efectuados únicamente en nuestras Oficinas Comerciales.

No.08SD000U02900231
RR DONNELLEY DE EL SALVADOR KM 7 1/2 BLVD DEL EJERCITO REG.51-5
TIRAJE DEL 08SD000U1 AL 08SD000U4000000 16 JUN 2008
No. DE AUTORIZACION DE NUMERACION CORRELATIVA: 10115-RES-CR-18948-2008

COMPROBANTE DEL CLIENTE

RR DONNELLEY DE EL SALVADOR S.A. DE C.V. TEL.: 2294-6400 1230630008.F1ORAM 030404

202

Favor no sellar ni escribir sobre el código de barras

Figure A24: Copy of the electricity bill for the month of May in Las Delicias, El Salvador. All costs are associated with power the current hydraulic system and this data is applied to the cost assumptions.

Café con Pan

ADESCO LAS DELICIAS SAN JUAN OPICO — EDUCACIÓN TRABAJO PAZ ECOLOGÍA

BOLETIN MENSUAL DE LA ADESCO CANTÓN LAS DELICIAS, SAN JUAN OPICO, LA LIBERTAD, EL SALVADOR.

28 de febrero de 2010 • Tiraje: 500 ejemplares • Año: I • Nº 0011

IMPORTANTE!!

El año pasado vinieron a Las Delicias representantes de Ingenieros sin Frontera (organización de Estados Unidos, que trabaja en los países más pobres del mundo con proyectos de desarrollo comunitario). En esa visita, la Directiva les presentó algunos proyectos; ellos a la vez manifestaron que si el proyecto se da, vendrían para trabajar con la gente, asesorando, brindando materiales; pero es la comunidad que tiene que trabajar.

Al parecer, el proyecto fue aprobado pues en febrero se comunicaron con la Directiva diciendo que a principios de marzo vendrá uno de ellos con el fin de trabajar en la comunidad. Si estos proyectos se dan, se lograría un gran desarrollo en nuestra comunidad. Pero necesitamos del trabajo de todos y todas. Sabemos que contamos con ello.

Junta Directiva Las Delicias.

CONSOLIDADO DE INGRESOS Y EGRESOS DEL MES DE ENERO, ADESCO LAS DELICIAS

SALDO AL 31 DE DICIEMBRE DE 2009			$1,388.87
INGRESOS		$2,003.40	
Cuota de agua del 4 al 31 de enero	$2,003.40		
EGRESOS		$2,362.00	
Transporte	$ 11.00		
Viáticos	$ 40.00		
Alquiler casa PNC (oct-nov-dic)	$ 75.00		
Papelería y fotocopias	$ 33.00		
Reparaciones	$ 114.00		
Energía	$1,106.55		
Materiales	$ 14.95		
Sueldos	$ 285.00		
Mano de obra (2do abono a mantenimiento y limpieza de pozo)	$ 500.00		
Otros gastos	$ 182.50		
Total de ingresos menos egresos (saldo deudor)		($ 358.60)	($ 358.60)
SALDO AL 31 DE ENERO DE 2010			$1,030.27

Gasto $1,500.—
Dic- 400.—
Ene 500.—
feb. 600.—

Fredy Montano
Presidente JD ADESCO

Dora Alicia Martinez
Tesorera JD ADESCO

Prontuario del Mes. MARZO	
Reunión de Becados.	7
Día Internacional de la mujer.	8
Día Internacional contra la discriminación racial. Reunión JD ADECO	21
Día internacional del agua	22
30 Aniversario del martirio de Mons. Oscar Arnulfo Romero.	24

NOTICIAS LOCALES

Edenilson Castro

Nueva Directiva en Las Delicias.

Presidente: Fredy Montano, 100 votos a favor.
Vicepresidente: Santiago Acosta, 84 votos.
Tesorera: Dora Alicia Martínez, 95 votos.
Protesorero: David Ramírez, 67.
Secretario: Edenilson Castro, 76.
Prosecretario: Mauricio Barrera, 79.
Síndico: Rosa Ruano, 60.
Vocal 1: Jorge Girón, 24.
Vocal 2: Mauricio López, 12.
Vocal 3: Betty Bolaños, 9.

El pasado domingo 31 de enero se realizaron las elecciones de la nueva Junta Directiva de Las Delicias.

Según asistencia que se tomó, estuvieron presentes 130 personas en la actividad. Se acordó que para aprobar la elección de un candidato como también de un proyecto se tomaría en cuenta la mitad de los asistentes mas uno, es decir 66 votos para ambos casos.

Acuerdos en Asamblea.

Los acuerdos que se tomaron en la Asamblea de enero fueron los siguientes:

Se aprobó el informe económico que presentó la tesorera. Se acordó continuar pagando el local de la PNC; que el valvulero actual continúe trabajando y con el mismo salario; además que don Chente continúe en la Bomba; que se mantenga el cobro de $5 dólares de agua y que este Boletín Informativo continúe funcionando. Con respecto a la solicitud de los deportistas de regar la cancha de fútbol durante el verano, no se les concedió esa petición.

La actividad finalizó con la rifa que estaba pendiente.

Figure A25: Copy of the monthly newsletter currently distributed by the management team of the hydraulic system. This data was used in determining the operations and maintenance costs of running the new hydraulic system.

Revenue Assumptions		
Parameter	**Value**	**Unit**
Current		
People/Household	6	
Bad Debt	0.1	
Monthly Elec Payment	$ 5.00	per family/month
Valle		$/kWh
Resto	0.1558	$/kWh
Punta	0.1206	$/kWh
Productivity Gain	1%	
GNI Per Capita (Wiki)	$ 1,080	
Pop. Growth Rate	0.332	%
Child Percentage	0.354	%
Adult Percentage	0.593	%
Elderly Percentage	0.053	%
Initial Population	3010	
Electricity Payments	1200	$/month
Current System Overhead %	45%	

Cost Assumptions		
Parameter	**Value**	**Unit**
Power System		
Discount Rate	10%	
O&M Cost	0.30%	
Inverter Life	10 years	yrs
Installed Cost	$.17/Wdc	
Other/Indirect Cost	$.76/Wdc	
Surcharges	398.43	$/month
Batteries	$ 25,376	$
Combiner Box	$ 200	$
AC Breaker Panel	$ 160	$
Inverter Cost	$ 500	$
BOS (Panels) Cost	$ 0.65	$/W
Maximum Power	63,133	W
Solar Charge Controller	$ 60	$
Hydraulic System		
Initial Costs		
Investment Cost	$ 21,609	$
Tank	$ 17,000	
Sub Pump Replacement	6000	8
Booster Pump Replacement	4175	5
O&M Costs	Cost (3 Pumps)	Time (yrs)
Well Cleaning	1500	1
Pump Cleaning	2503.5	2
General Maintenance	171	0.833
Pipe maintenance	135	0.667
Pumper Salary	5130	1
Valver Salary	5130	1
Material Expenses	900	1

Table A26: Las Delicias, El Salvador. Table of revenue and cost assumptions applied to financial calculations. Assumptions are discussed in detail in the Revenue and Cost Assumptions section.

	25.5 kW	Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Current system	**Revenue**	**Current Payments**	$ 27,000	$ 27,090	$ 27,180	$ 27,279	$ 27,378	$ 27,477	$ 27,576	$ 27,675	$ 27,774	$ 27,873	$ 27,972	$ 28,071	$ 28,170	$ 28,269	$ 28,368	$ 28,467	$ 28,566	$ 28,665	$ 28,764	$ 28,863
			$ 558,477																			
		Overhead	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146	$ 7,146
		Electricity Cost	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879	$ 15,879
			$ 460,489																			
		Population	3000	3010	3020	3031	3042	3053	3064	3075	3086	3097	3108	3119	3130	3141	3152	3163	3174	3185	3196	3207
		Children	1062	1066	1070	1073	1077	1081	1085	1089	1093	1097	1101	1105	1109	1112	1116	1120	1124	1128	1132	1136
		Adults	1779	1785	1791	1798	1804	1811	1817	1824	1830	1837	1844	1850	1857	1863	1870	1876	1883	1889	1896	1902
		Elderly	159	160	161	161	162	162	163	163	164	165	165	166	166	167	168	168	169	169	170	170
Power System	**PV System**	**Investment**	$ 41,036	-	-	-	-	-	-	-	-		$ 500	-	-	-	-	-	-	-	-	
		Batteries	$ 24,450	-	-	-	-	-	-	-	-	-	$ 24,450	-	-	-	-	-	-	-	-	
		Instillation	$ 4,335	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Other/Indirect	$ 9,690	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		O$M	$ 239	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196
		Total	$ 79,750	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 25,146	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196	$ 196
			$ 108,433																			
	Pumps	Pump Investment	$ 21,609	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Tank Cost	$ 17,000																			
		Well Cleaning	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500
		Pump Cleaning	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5	-	2503.5
		General Maintenance	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5	142.5
		Pipe maintenance	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
		Pumper Salary	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130
		Valver Salary	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130	5130
		Material Expenses	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
		Sub Pump Replacement	-	-	-	-	-	-	-	6000	-	-	-	-	-	-	-	6000	-	-	-	-
		Booster Pump Replacement	-	-	-	-	4175	-	-	-	-	4175	-	-	-	-	4175	-	-	-	-	4175
		Total	$ 51,502	$ 15,396	$ 12,893	$ 15,396	$ 17,068	$ 15,396	$ 12,893	$ 21,396	$ 12,893	$ 19,571	$ 12,893	$ 15,396	$ 12,893	$ 15,396	$ 17,068	$ 21,396	$ 12,893	$ 15,396	$ 12,893	$ 19,571
			$ 350,194																			
Summary		Revenues	$ 27,000	$ 27,090	$ 27,180	$ 27,279	$ 27,378	$ 27,477	$ 27,576	$ 27,675	$ 27,774	$ 27,873	$ 27,972	$ 28,071	$ 28,170	$ 28,269	$ 28,368	$ 28,467	$ 28,566	$ 28,665	$ 28,764	$ 28,863
		Productivity Gain	$ 19,213	$ 19,278	$ 19,343	$ 19,418	$ 19,483	$ 19,559	$ 19,624	$ 19,699	$ 19,764	$ 19,840	$ 19,915	$ 19,980	$ 20,056	$ 20,120	$ 20,196	$ 20,261	$ 20,336	$ 20,401	$ 20,477	$ 20,542
		Costs	$ 131,251	$ 15,592	$ 13,089	$ 15,592	$ 17,264	$ 15,592	$ 13,089	$ 21,592	$ 13,089	$ 19,767	$ 38,039	$ 15,592	$ 13,089	$ 15,592	$ 17,264	$ 21,592	$ 13,089	$ 15,592	$ 13,089	$ 19,767
		Cash Flows	$ (85,038)	$ 30,776	$ 33,434	$ 31,105	$ 29,597	$ 31,443	$ 34,111	$ 25,782	$ 34,449	$ 27,945	$ 9,848	$ 32,459	$ 35,137	$ 32,797	$ 31,300	$ 27,135	$ 35,813	$ 33,474	$ 36,152	$ 29,637
		Present Value	$ (85,038)	$ 30,291	$ 32,389	$ 29,658	$ 27,776	$ 29,044	$ 31,012	$ 23,070	$ 30,341	$ 24,225	$ 8,403	$ 27,258	$ 29,043	$ 26,682	$ 25,063	$ 21,386	$ 27,781	$ 25,557	$ 27,167	$ 21,921
		NPV	$ 413,029																			
		IRR	36%																			

Figure A27: Forward looking financial model for revenues, costs and cash flows. The information is calculated to assumptions disclosed in Table 1.

Revenue Assumptions		
Parameter	**Value**	**Unit**
Productivity Gain	2%	
GNI Per Capita	$ 1,200	
Working Age Percentage	59%	%
Initial Population	750	

Cost Assumptions		
Parameter	**Value**	**Unit**
Power System		
Discount Rate	10%	
O&M Cost	0.30%	
Inverter Life	10 years	yrs
Installed Cost	$.17/Wdc	
Other/Indirect Cost	$.38/Wdc	
Combiner Box	$ 200	$
AC Breaker Panel	$ 160	$
Inverter Cost	$ 500	$
BOS (Panels) Cost	$ 0.69	$/W
Maximum Power	20,000	W
Solar Charge Controller	$ 60	$
Hydraulic System		
Initial Costs		
Investment Cost	$ 7,487	$
Pump Replacement	$ 7,487	8
O&M Costs	Cost (1 Pump)	Time (yrs)
Well Cleaning	750	1
Pump Cleaning	834.5	2
General Maintenance	57	0.833
Pipe maintenance	45	0.667
Pumper Salary	1200	1
Valver Salary	1200	1
Material Expenses	300	1

Table A28: Relevant financial assumptions for the power and hydraulic systems in Apatut, the Philippines. These assumptions are used to generate the revenues, cost, cash flows, Net Present Value, and Internal Rate of Return for this project.

	4.02 kW	Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Power System	PV System	Investment	$ 13,800	-	-	-	-	-	-	-	-	$ 500	-	-	-	-	-	-	-	-	-	$ 500
		Batteries		-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	
		Instillation	$ 683	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Other/Indirect	$ 1,018	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		O$M	$ 47	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41
		Total	$ 15,548	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 541	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 41	$ 541
			$ 17,335																			
Hydraulic System	Pumps																					
		Investment	$ 7,487	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Well Cleaning	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750	$ 750
		Pump Cleaning	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5	-	834.5
		General Maintenance	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5
		Pipe maintenance	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
		Pumper Salary	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
		Valver Salary	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
		Material Expenses	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
		Pump Replacement	-	-	-	-	-	-	-	$ 7,487	-	-	-	-	-	-	-	$ 7,487	-	-	-	-
		Total	$ 11,015	$ 4,362	$ 3,528	$ 4,362	$ 3,528	$ 4,362	$ 3,528	$ 11,849	$ 3,528	$ 4,362	$ 3,528	$ 4,362	$ 3,528	$ 4,362	$ 3,528	$ 11,849	$ 3,528	$ 4,362	$ 3,528	$ 4,362
			$ 101,356																			
Summary		Productivity Gain	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620	$ 10,620
		Costs	$ 26,563	$ 4,403	$ 3,569	$ 4,403	$ 3,569	$ 4,403	$ 3,569	$ 11,890	$ 3,569	$ 4,903	$ 3,569	$ 4,403	$ 3,569	$ 4,403	$ 3,569	$ 11,890	$ 3,569	$ 4,403	$ 3,569	$ 4,903
		Cash Flows	$ (15,943)	$ 6,217	$ 7,051	$ 6,217	$ 7,051	$ 6,217	$ 7,051	$ (1,270)	$ 7,051	$ 5,717	$ 7,051	$ 6,217	$ 7,051	$ 6,217	$ 7,051	$ (1,270)	$ 7,051	$ 6,217	$ 7,051	$ 5,717
		Present Value	$ (15,943)	$ 6,119	$ 6,831	$ 5,928	$ 6,617	$ 5,742	$ 6,411	$ (1,137)	$ 6,210	$ 4,956	$ 6,016	$ 5,221	$ 5,828	$ 5,057	$ 5,646	$ (1,001)	$ 5,470	$ 4,746	$ 5,299	$ 4,228
		NPV	$ 78,243																			
		IRR	39.08%																			

Figure A29: Forward looking financial model for revenues, costs and cash flows. The information is calculated to assumptions disclosed in table 1.

Table A30. Approximate thermal stability of selected molten nitrate and nitrate-nitrite salt mixtures. Compositions are given as mole%, cation basis. The temperature values refer to melts in contact with air.

Na	**K**	**Ca**	**Li**	**Other**	**Maximum Temp.**
mole %	mole %	mole %	mole %	mole %	°C
66	34				600
7	44			49 $NaNO_2$	450 to 538
18	45		37		550
30	50	20			505
20	50	30			480
High	+	+	+		~520
Med	+	+	+		~520
Low	+	+	+		~520
18	45		37		>540

Calculations

Power calculations

This section includes all relevant formulas used to determine information used in designing the photovoltaic power system. All of the constants and data available are included in the next section, Tables and Figures. The data for this project is presented with units from the International System of Units (SI), the modern form of metric units.

Basic electromotive force definitions are needed to understand the relationships between the different components of the PV power system.

Table of Definitions

Measurement	Units	Definition
Charge (C)	Coloumb	A*t
Current (I)	Amperes	1 C/s
Power (P)	kW	I*V
Energy (E)	kWh	P*t
Voltage (V)	Volts	W/A

To calculate the total power of a single solar module consisting of multiple panels, Equation 1 was used.

$$p_{max} = p_{panel} * \eta * n$$ Equation A1

Where,

p_{max} = maximum power provided by each module
p_{panel} =maximum power of the panel at STC
η=efficiency of the solar cells
n= panels per module

The actual amount of power supplied by a solar module at any given time is given by multiplying the maximum power by the actual insolation incident on the panel. As all the panels will be oriented horizontally, the horizontal incident is applicable.

$$p_t = p_{max} * i_t$$ Equation A2

Where,

p_t = power supplied at time t

i_t = insolation incident on a horizontal surface at time t

The minimum number of modules required to power any given load at any time is given by equation 3. The number is rounded up to the nearest whole number as fractions of solar modules are not applicable.

$$m_t = p_{load}/p_t \qquad \text{Equation A3}$$

Where,

m = number of modules required to power load at time t

p_{load} = power required by load

The total amount of energy generated by the modules was calculated by summing the power provided over the course of daylight hours.

$$E_{tot} = M * \sum_{t=9}^{18} p_t \qquad \text{Equation A4}$$

Where,

E_{tot} = Total energy provided throughout the day

M = number of modules in the system

Hydraulic Calculations

This section includes all of the formulas used to calculate TDH. All of the calculated data is presented under *Tables and Figures. The* data given for this project was measured in metric units; consequently, all of the constants and any given figures will be reported in metric units. English units were needed to determine pump size, as all of the performance curve obtained were in English units. Therefore, the calculated data is reported in English units, as are the plots and figures that accompany all numerical results. Conversions were not shown in these calculations.

The Total Dynamic Head is the total head that the pump must overcome. It includes static height and head loss. The static height calculations are based on the elevation difference between the point where the water is located in the well and the point where the water enters the tank.

The head loss is associated with the extra head the pump has to overcome due to friction in the pipes. The calculations were based on the metric system, but the final numbers are reported in English units. This is because the data available was in metric units, whereas the units used for most pump performance curves were in English units. The Darcy – Weisbach equation for calculating head loss is presented as equation 2:

$$h_f = 2 * f_F * \frac{L}{D} * \rho * v^2 \qquad \text{Equation A5}$$

Where,

h_f = head loss [m]
f_F = Fanning friction factor
L = length of pipe [m]
D = diameter of pipe [m]
ρ = fluid density [kg/m^3]
v = fluid velocity [m/s]

The Fanning friction factor was based on turbulent flow and calculated using equation 3:

$$f_F = \{-1.737 * \ln\left[0.269 * \frac{\varepsilon}{D} - \frac{2.185}{Re} * \ln\left(0.269 * \frac{\varepsilon}{D} + \frac{14.5}{Re}\right)\right]\}^{\wedge -2} \qquad \text{Equation A6}$$

Where,

ε = surface roughness of pipe [m]
Re = Reynolds number

The Reynolds number was found using equation 4:

$$Re = \frac{\rho v D}{\mu} \qquad \text{Equation A7}$$

Where,

μ = fluid viscosity [kg/m-s]

The velocity was calculated based on equation 5:

$$v\ [{}^{m}/_{s}] = \frac{Q}{A * 3600} \qquad \text{Equation A8}$$

The number and type of fittings was approximated for both projects, as detailed data was not provided. It was determined that in both cases, the fittings contributed less than 1% to the TDH, leading us to be confident in our estimation techniques.

The TDH and Q were used to develop a system curve for each section of individual systems. These are presented under *Tables and Figures.*

To determine an appropriately sized pump for the system, we calculated the power requirement for specific TDH and flow rates, Q. The pump power requirement was determined using equation 6:

$$[HP] = \frac{GPM\ x\ Head\ (ft) x\ Specific\ Gravity}{3960\ x\ Pump\ efficiency} \qquad \text{Equation A9}$$

In our calculation of pump horsepower, we assumed a pump efficiency of 60% for all pumps in both projects. Pump efficiency range from 35% to 90% depending on the motor size and the operating flow rate. For most of the pumps we looked at, the pumps were within the range of 50% - 75%, and so estimating an overall pump efficiency of 60% was appropriate. In the case where we might have underestimated the efficiency, we expect the real flow rate under field conditions to be greater than expected, provided that the solar panels will be able to produce enough power.

The following constants were used during calculations:

Table of Constants

Constants		
Symbol	Unit	Value
μ	kg/m-s	0.001002
ρ	kg/m^3	1000
ε	PVC (m)	0.0000460
	Steel (m)	0.0000015
g	m/s^2	9.81
η	-	0.6

Table of Pump Constants

Pump	Pipe type	L	(L/D)	D	
		[m]	-	[in]	[m]
Submersible	Section 1	66	-	6	0.1524
	Standard 90 elbow	-	30	6	0.1524
	Section 2	3538	-	6	0.1524
Booster to tank 1	Section 1	1995	-	2.5	0.0635
	Standard "T" through side outlet	-	70	-	-
Booster to tank 3	Section 1	1032	-	4	0.1016
	Standard "T" through side outlet	-	70	-	-
	Section 2	1044	-	3	0.0762